Aalto University
School of Science
Master's Programme in Engineering Physics

Antti Ukkonen

Potential consequences of hypothetical domestic nuclear power plant accidents

Master's Thesis

Thesis submitted for examination for the degree of Master of Science in Technology.
Helsinki, 22.5.2019

Supervisor: Professor, D.Sc. (Tech.) Filip Tuomisto
Advisor: Head of Laboratory, Ph.D. Aleksi Mattila

Aalto University
School of Science

Aalto University
School of Science
Master's Programme in Engineering Physics

ABSTRACT OF MASTER'S THESIS

Author:	Antti Ukkonen		
Title: Potential consequences of hypothetical domestic nuclear power plant accidents			
Date:	22.5.2019	**Pages:**	vii + 59
Major:	Applied Physics	**Code:**	SCI3056
Supervisor:	Professor, D.Sc. (Tech.) Filip Tuomisto		
Advisor:	Head of Laboratory, Ph.D. Aleksi Mattila		

Knowledge of the potential consequences of a nuclear power plant accident is an important aspect on emergency preparedness. The protective actions during a nuclear emergency are based on the radiological consequences of the release. This thesis studies three hypothetical nuclear power accident scenarios with different magnitudes. The operating Finnish power reactor units Loviisa 1&2 and Olkiluoto 1&2 are included in the study. Modeling of the consequences is based on historical weather data from years 2012-2015 retrieved with AROME and HARMONIE operative weather forecast models. Dispersion and deposition calculations are done with SILAM dispersion model. Dose rates and doses are calculated with threat assessment tool TIUKU, developed by the Finnish Radiation and Nuclear Safety Authority. Post-processing of the data is done with Python and its computational libraries. The results are compared to operational intervention levels and dose criteria. The sufficiency of emergency planning zones (EPZs) is analysed as well. Comparison shows that the protective actions are needed outside the emergency planning zones in the worst scenario studied, otherwise the EPZs suite the studied scenarios.

Keywords:	Nuclear power plant accident, protective actions, emergency preparedness, SILAM, emergency planning zones, operational intervention levels
Language:	English

Aalto-yliopisto
Perustieteiden korkeakoulu
Master's Programme in Engineering Physics

DIPLOMITYÖN TIIVISTELMÄ

Tekijä:	Antti Ukkonen		
Työn nimi: Hypoteettisten ydivoimalaitosonnettomuuksien mahdolliset seuraukset kotimaisissa ydinvoimalaitoksissa			
Päiväys:	30. kesäkuuta 2019	**Sivumäärä:**	vii + 59
Pääaine:	Teknillinen fysiikka	**Koodi:**	SCI3056
Valvoja:	Professori, TkT Filip Tuomisto		
Ohjaaja:	Laboratorionjohtaja, FT Aleksi Mattila		

Tietämys ydinvoimalaitosonnettomuuden mahdollisista seurauksista on tärkeä osa onnettomuuksiin varatumisessa. Suojelutoimet ydinvoimalaitosonnettomuuden aikana pohjautuvat päästön säteilyvaikutuksiin. Tämä diplomityö tutkii kolmea eri suuruusluokan hypoteettista voimalaitosonnettomuusskenaariota Suomen käyvillä laitosyksiköillä Loviisa 1&2 sekä Olkiluoto 1&2. Vaikutusten arviointi perustuu todelliseen säädataan vuosilta 2012-2015, joka on kerätty operatiivisilla AROME- ja HARMONIE-sääennustusmalleilla. Leviämislaskut ja laskeumat on laskettu käytteän SILAM-leviämismallia. Annosnopeudet ja annokset on laskettu Säteilyturvakeskuksen uhka-arviotyökalu TIUKUlla. Tulosten jälkikäsittely on tehty Pythonilla sen laskennallisia kirjastoja käyttäen. Saatuja tuloksia verrataan operatiivisiin toimenpidetasoihin ja annoskriteereihin. Lisäksi varautumisalueiden riittävyyttä arvioidaan. Vertailu osoittaa, että vakavimmassa tutkitussa onnettomuustapauksessa suojelutoimia tarvitaan varautumisalueen ulkopuolella. Muissa tapauksissa varautumisalue todettiin riittäväksi.

Asiasanat:	Ydinvoimalaitosonnettomuudet, suojelutoimenpiteet, valmius, varautuminen, SILAM, varautumisalueet, operatiiviset toimenpiderajat
Kieli:	Englanti

Acknowledgements

This Master's Thesis is done for the purposes of Finnish Radiation and Nuclear Safety Authority (STUK) during the time between October 2018 and May 2019. First I would like to thank my advisor Aleksi Mattila for his guidance during this project. Thank you to my supervisor professor Filip Tuomisto for supervision and support in my final studies. Another big thanks goes to my colleagues Tuomas Peltonen for all the work on the calculations and to Tarja Ilander for helping me to make a decent map. My project would not have been possible without STUK's threat analysis work group, and especially the expertise of Tomi Routamo in the field of NPP source terms. Special thanks are in order to my every day colleagues and section head at STUK's Emergency Preparedness unit. Thank you Hannele, Juku, Antero, and Hanna. Also thanks to my colleague Eetu for all the conversations, coffee breaks, and support in and out of office.

My journey at Aalto University started at the Guild of Physics in 2011. Now the journey is finally ending. Thanks to all the physicist and other friends for the past years. Special thanks goes to ITMK13, Raati3, and Fyysikkospeksi.

Thanks to my parents for all their support in education and life in general. Finally I want to thank my beloved partner in love and crime, Sasu. Without your support, I could not have pushed through my final studies.

Helsinki, 22.5.2019

Antti Ukkonen

Contents

Acronyms and abbreviations

Bq	becquerel
EPZ	Emergency Plannig Zone
EC	Electron Capture
eV	electronvolt
FMI	Finnish Meteorological Institute
Gy	gray
LET	Linear Energy Transfer
LOCA	Loss of Coolant Accident
NPP	nuclear power plant
OIL	Operational Intervention Level
PAZ	Precautionary Action Zone
SSM	Swedish Radiation Safety Authority
STUK	Radiation And Nuclear Safety Authority (of Finland)
Sv	sievert
UPZ	Urgent Protective action planning Zone

Chapter 1

Introduction

Using nuclear power always includes a risk of a radioactive release. All the risks are to be minimized so that the benefits of the nuclear power are greater than the unwanted consequences to the society. This thinking is based on the so called principle of justification from the Radiation Act [1]. In case there would be a nuclear or radiological emergency, there has to be an emergency plan according to Finnish Emergency Powers Act [2] and Rescue Act [3]. To define proper protective actions and to prepare for emergency situations, authorities require a proper analysis on possible threats and their effects on environment and people. In Finland, Radiation and Nuclear Safety Authority (STUK) is the competent authority on nuclear and radiological emergencies, which provides expertise and recommendations to rescue services and governmental authorities which have the decision making power on protective actions considering the population and the society in general.

1.1 Objective

The objective of this master's thesis is to offer material to STUK's work on preparedness regarding nuclear power plant (NPP) accidents. Nuclear power plant accidents are impossible to predict accurately. It is difficult to predict dispersion of the possible radioactive release due to inaccuracies of the weather forecast models and overall nature of weather conditions as well as due to uncertainty of the release time and duration.

1.2 Previous research

Previous report on nuclear power plant threats considering Finland was made in 1993 about the risks of the Sosnovyy Bor nuclear power plant in Leningrad, Russia [4]. Report was published by Finnish Radiation and Nuclear Security Authority STUK in collaboration with Finnish Meteorological Institute. The scope of the report was short term radiological consequences in Southern-Finland in case of a hypothetical severe reactor accident. In 1994 Technical Research Center of Finland VTT published a report as well on Sosnovyy Bor [5]. The topic of the report was radiation risks considering the NPP.

In 2011 STUK published an update considering the report published in 1993 [6]. The report update includes five other NPP locations amongst Sosnovyy Bor: Loviisa and Olkiluoto in Finland, Kola in Russia, Ingnalina in Lithuania, and Forsmark in Sweden.

Swedish Radiation Safety Authority (SSM) published a *Review of Swedish emergency planning zones and distances* in 2018 [7]. In the review SSM studied postulated nuclear events on their NPPs at Forsmark, Oskarshamn, and Ringhals. SSM made suggestions to change emergency planning zones (EPZs) so that the precautionary action zone (PAZ) would be an area with 5 km radius from the NPP and urgent protective action planning zone (UPZ) would have 25 km radius.

1.3 Structure of the thesis

This thesis is structured so that the chapter 2 introduces different types of ionizing radiation and their biological effects. In chapter 3 the basics of nuclear reactors and radioactive materials in them are presented within the scope of this thesis. Chapter 3 presents also the dispersion and deposition of radioactive materials. Chapter 4 introduces the preparedness for a nuclear emergency and protective actions during a NPP accident in Finland.

Chapters 5-6 presents the methods used in data analysis. Chapter 5 describes how the modeling of the weather, and dispersion and dose calculations were executed. In chapter 6 the accident scenarios and the source terms used in them are introduced. In chapter 7 the post-processing methods of the calculated data are introduced.

In chapter 8 the results are shown and discussed. Comparison to current protective action operational intervention level values and NPP EPZs are made. Chapter 9 concludes the results and discusses the future research prospects. The 10th and final chapter summarizes the topics and results of this thesis.

Chapter 2

Ionizing radiation

Ionizing radiation is highly energetic and able to change the electric charge of atoms i.e. ionize them. This radiation originates from *radioactive decay*, *nuclear reactions*, or from the activity at the atom's electron sheath. When energy of ionizing radiation is absorbed by human tissue, it causes chemical changes and has negative biological consequences [8]. Ionizing radiation is divided into electromagnetic radiation as gamma and X-rays, and particle radiation as alpha and beta rays, and neutron radiation.

This chapter introduces the properties of ionizing radiation – beginning with radioactive decay in section 2.1. In section 2.2 the units of measure considering radiation, and relevant to this thesis, are introduced. Section 2.3 discusses the effects of the radiation on humans and environment, stating the reasons why protective actions are in place in case of a radioactive release. How these radioactive materials disperse and deposit is the basis on these protective actions. These are discussed in section 3.4.

2.1 Radioactive decay

There are some nuclei in nature that are unstable, which means they spontaneously alternate into other nuclei without any external triggers [8]. An aspect effecting to the stability is neutron-proton ratio of the nucleus. When the number of protons increases over 83, the electromagnetic forces on the positive particles create a repulsion that makes the stability of the nucleus impossible [9]. This means that elements with atomic number $Z \geq 84$ are not stable and hence are called radioactive elements. These elements emit energy to reach a more stable configuration [10]. Another way to express stability properties is by binding energy of the nucleus. Binding energy Q describes how much energy is needed to separate the nucleons of a certain nucleus. The ratio between Q and mass number A tells how stable the nucleus is. When Q/A is large, the nucleus is stable [11]. Figure 2.1 illustrates this ratio, and shows how the mid-mass and heavy nuclei has the highest ratio. Iron-56 (^{56}Fe) has the highest energy per nucleon – approximately 8.6 MeV.

The decay process is called *radioactive decay*. The decaying nucleus is called parent nucleus and the resulting nucleus the daughter nucleus. In the decay process the parent nucleus emits particles and/or photons.

Figure 2.2 shows the schematic illustrations of basic radioactive decay processes: alpha decay, beta decay, and gamma decay. These are introduced in more detail in sections 2.1.1-2.1.3.

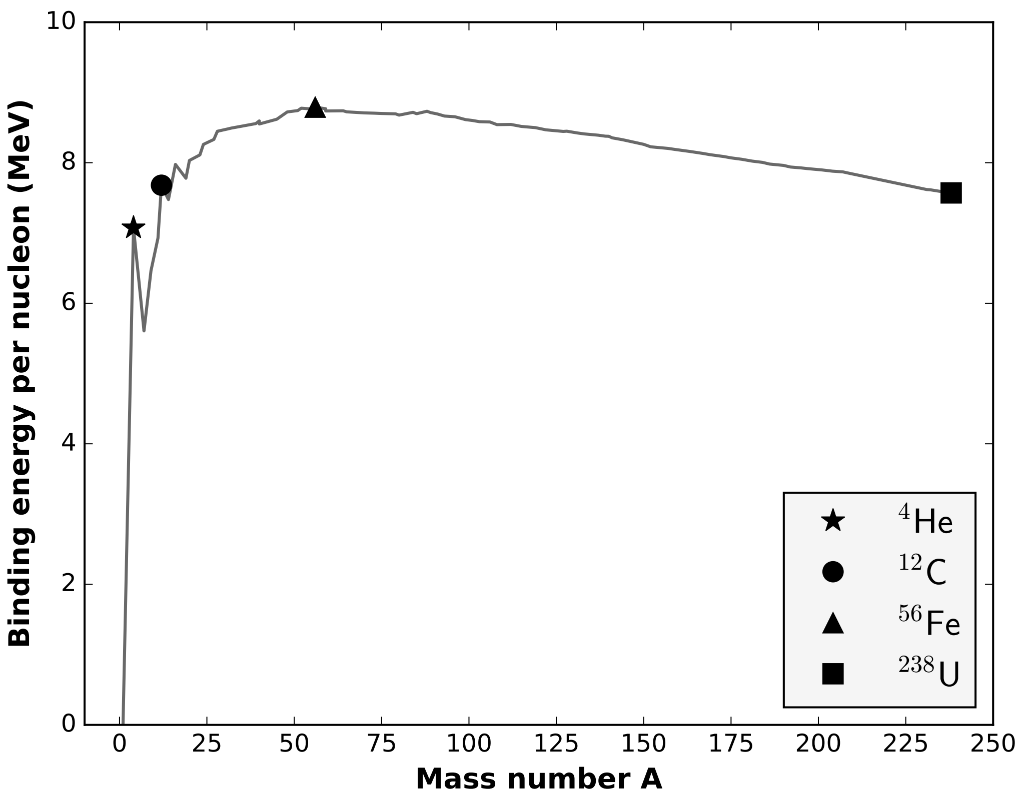

FIGURE 2.1: Binding energy per nucleon as a function of mass number A [12].

2.1.1 Alpha decay

Alpha decay occurs on heavy nuclides that are unstable. Those nuclides emit a nucleus of an ionized helium-4 atom, ${}^4_2$He [11]. The daughter nuclide might be in an excited state and emits electromagnetic radiation when returning to ground state. Each alpha active nuclide emits alpha nuclides at the same energy or the energies are divided to a few different energy groups.

The alpha decay induced radiation is densely ionizing [11]. Alpha particle loses its kinetic energy in inelastic collisions [8]. It has mass of over 7000 electrons, so it goes straight forward in the medium without scattering. Due to alpha particle's high mass and charge, a medium is able to decelerate α-particle effectively. Hence the range of an alpha particle is short. For example in the air, the range R (in centimeters) of an α-particle with energy E (in MeV) can be estimated under normal temperature and pressure with formula [8]

$$\begin{aligned} R_{\text{air}} &= 0.56 \cdot E, && \text{when } E < 4 \text{ MeV} \\ R_{\text{air}} &= 1.24 \cdot E - 2.62, && \text{when } 4 \text{ MeV} < E < 8 \text{ MeV}. \end{aligned} \tag{2.1}$$

If the medium is other than air, the range is expressed in area-mass units (in mg/cm^2) is

$$R_\rho = 0.56 A_r^{1/3} R_{\text{air}}, \tag{2.2}$$

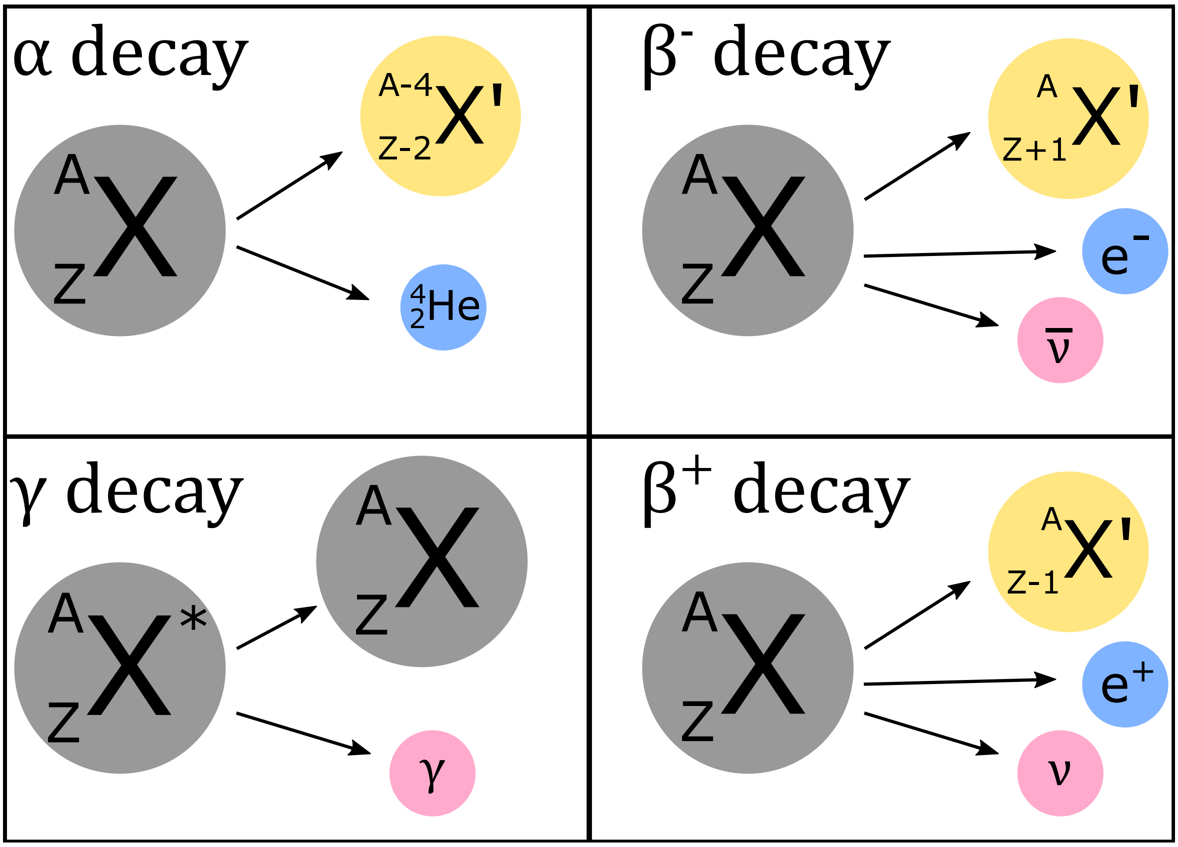

FIGURE 2.2: Schematics of basic radioactive decay processes, where ${}^{4}_{2}$He refers to alpha particle, ν to neutrino and $\bar{\nu}$ to antineutrino, e^- to electron and e^+ to positron, and γ to gamma ray.

where $A_r^{1/3}$ is relative atomic mass of the medium.

These equations show how the α-radiation acts in different media. In air the range of 6 MeV alpha particle is approximately 4.6 cm and in tissue it is 56 μm.

2.1.2 Beta decay

In the beta decay the nucleus returns to the lower energy state so that the charge of the nucleus changes but the mass number does not [8]. Beta decay can be divided into three categories: β^+ and β^- decay, and electron capture.

Beta decay occurs when one neutron in a nucleus decays into proton and electron (β^--decay) or one proton decays into neutron and positron (β^+-decay) [8]. The actual radiation is when the electron or the positron is emitted from the nucleus in the decay process. In addition, the electron (or the positron) annihilates with positron (or electron). In annihilation two gamma quanta are emitted. In the electron capture (EC) nucleus literally captures an electron from the electron sheath. An electron from upper electron shell fills the void left by the captured electron, causing characteristic X-ray radiation.

Since electrons and positrons, β^-- and β^+-particles, are much lighter than alpha particles, they behave in a different matter in medium. The beta particles are sensitive to inelastic scattering, hence they lose their energy quickly and their trajectories are curvy and irregular.

The range of beta radiation is expressed in area-mass units as well. With maximum energy E the estimate for range is [8]:

$$R_\rho = \begin{cases} 0.412E^{1.254-\ln E}, & \text{when } 0.01 \text{ MeV} \le E \le 2.5 \text{ MeV} \\ 0.53E - 0.106, & \text{when } E > 2.5 \text{ MeV and } R_\rho > 1.2 \text{ g cm}^{-2} \end{cases} \tag{2.3}$$

2.1.3 Gamma radiation

Gamma radiation is a general expression for electromagnetic radiation induced by the changes in the energy state of a nucleus or nuclear transitions. The energy of a gamma quantum E_γ is the remainder of the energy of the exited state (E_1) and final energy state (E_2). The frequency f and wavelength λ can be calculated from that energy as well [8]:

$$E_\gamma = E_1 - E_2 = hf = \frac{hc}{\lambda}, \tag{2.4}$$

where h is Planck's constant and c is the speed of light in vacuum.

2.2 Radiation units and terminology

Radioactivity

Radioactive decay process is described by unit becquerel (Bq) [9]. Becquerel states how many decays occur in one second [13]. This can be formulated:

$$1 \text{ Bq} \equiv 1 \text{ nuclear disintegration per second.}$$

Becquerel is a small unit and it is common to express activity in kilobecquerel (kBq) or megabecquerel (MBq).

Dose

Another relevant property of ionizing radiation is its effect. Effects are estimated through dose values. Radiation dose expresses the amount of energy absorbed in radiation target material, e.g. human tissue [10]. An old unit for dose measurement is Gray (Gy), that is

$$1 \text{ Gy} \equiv 1 \text{ joule of absorbed energy per kg.}$$

When considering effects of ionizing radiation to biological systems *equivalent dose* is used. The energy of radiation causes damage to biological tissue. When the radiation is absorbed into a small area, the damage can be estimated with a *radiation weighting factor* w_r [10]. For high energy radiation, i.e. x-rays and γ-rays, the w_r is set to 1. For particle radiation, the $w_r > 1$. The biological effective dose, called the *equivalent dose* H, is defined as the product of the physical dose (in Gy) and w_r. The unit of the equivalent dose is sievert (Sv). H is mathematically expressed as

$$H = w_r \cdot D, \tag{2.5}$$

where D is the physical dose in grays.

Sometimes it is useful to calculate an estimate of *effective equivalent dose* E which is a sum of the products between equivalent doses affecting a certain human organ multiplied and weighting factor of that particular organ [10]. The formula for E is

$$E = w_1 H_1 + w_2 H_2 + \dots, \tag{2.6}$$

where w_i is a weighting factor of organ i and H_i its equivalent dose. The unit of the effective equivalent dose is sievert. The weighting factors of organs are listed in table 2.1

TABLE 2.1: Weighting factors for different organs [10, 14]

Organ	**Weighting factor w_i**
Gonads	0.20
Bone marrow, lungs stomach, colon	0.12
Bladder, breasts, liver, thyroid gland, esophagus and rest of the tissues	0.05
Skin, surface of the skin	0.01
Total	**1.0**

Dose rate

Dose rate $\dot{E}$ describes the change of the effective dose in unit Sv/s. The most practical unit in radiological events is Sv/h. Mathematical expression of the dose rate reads:

$$\dot{E} = \frac{\mathrm{d}E}{\mathrm{d}t}. \tag{2.7}$$

Half-life

When considering radioactive materials and their effects, it is useful to understand how the activity of the radioactive nuclei change in time. The statistical estimate of the time during which the activity has decreased into one half of the original is called *half-life* and marked shortly as $T_{1/2}$ [10]. The activity reduction as a function of time in half-lives is presented in fig. 2.3. This definition of half-life means *physical half-life*.

When considering radioactive material digested, inhaled, or otherwise taken into one's body, it is necessary to talk about *biological half-life*. This means the time when half of the radioactive isotopes have been eliminated from the body via the biological pathways – such as through kidneys, urine, and via perspiration [10]. Since the biological half-life is highly dependent on metabolism it cannot be precisely defined and it depends on personal features of the person examined.

In order to notice the significant difference between physical and biological half-lives, let us compare these values of ^{137}Cs. Its physical half-life is approximately 30 years but during the Chernobyl NPP accident in Ukraine in 1986 the biological half-life for an adult was defined to be approximately three months [10].

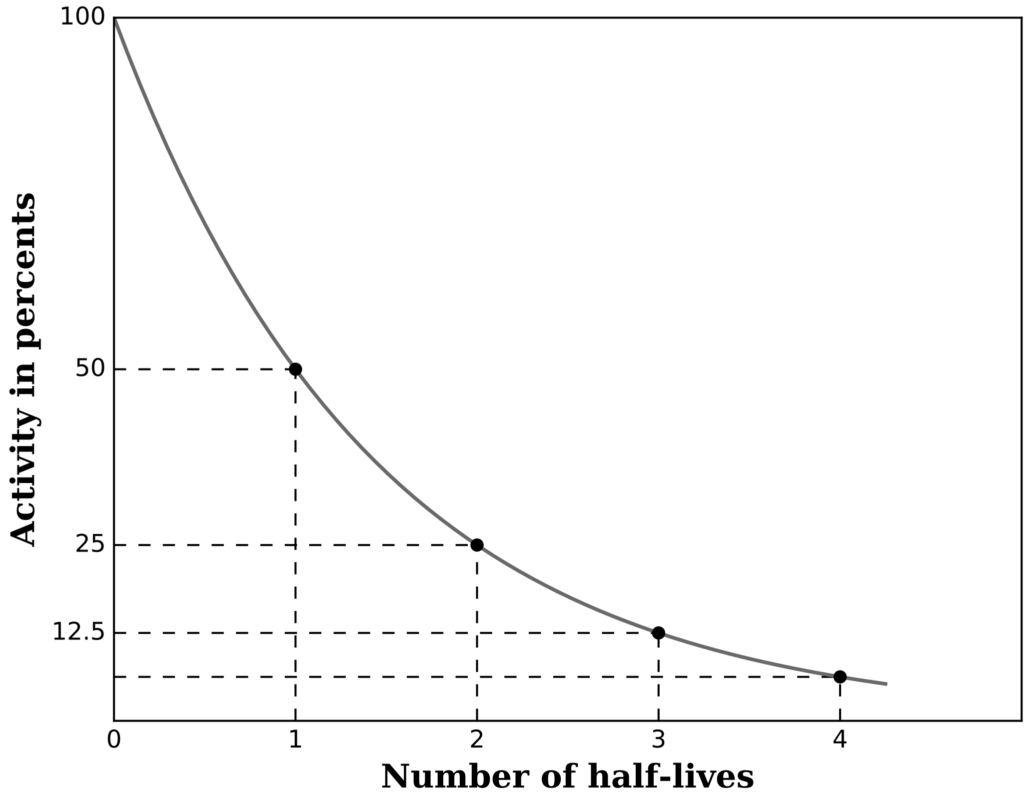

FIGURE 2.3: Radioactivity percentage as a function of half-life number.

The laws of radioactive decay

To calculate activity, A, of a nuclei, it is done by using formula [10]:

$$A = -\frac{\mathrm{d}N}{\mathrm{d}t} = \lambda \cdot N, \tag{2.8}$$

where N is the number of atoms, and dN describes the change in N during a time interval dt. λ is a *disintegration constant* characteristic to an isotope.

An equation of decrease in N can be derived from eq. 2.8 by integrating over time [10]:

$$N = N_0 \cdot e^{-\lambda t} \tag{2.9}$$

Furthermore half-life $T_{1/2}$ and λ are linked via the following equation when setting $N = \frac{N_0}{2}$:

$$T_{1/2} = \frac{\ln 2}{\lambda}. \tag{2.10}$$

2.3 Biological effects of ionizing radiation

The ionizing radiation effects literally with its ionizing impact on particles, e.g. human tissue. This section introduces the basic principles of these biological effects on humans.

The biological effects on human tissue is risen from the energy that is absorbed into the tissue from radiation. This energy causes physical changes which leads to chemical reactions, damaging the micro molecules of cells [15]. The different radiation types are divided roughly into sparsely and densely ionizing radiation, depending on their capability to transfer energy to the cells or other medium [16]. The energy deposited to the medium per length unit travelled in the medium is called *linear energy transfer* (LET). LET values of the densely ionizing radiation are thereby higher than the ones of sparsely ionizing [10]. Deposited energy per length unit, $\mathrm{d}E/\mathrm{d}x$, for particle radiation is described by the *Bethe formula*, which reads in a simplified form:

$$\frac{\mathrm{d}E}{\mathrm{d}x} \approx k\frac{z^2}{v^2}, \tag{2.11}$$

where k is coefficient simplifying more complex form of different constants, z is the charge of the moving particle, and v is its velocity.

As the sparsely ionizing radiation does not interact with medium, it has a longer range than densely ionizing radiation. Gamma and beta radiations are sparsely ionizing whereas alpha radiation is densely ionizing.

As mentioned in sec. 2.1.1 alpha radiation wiht energy of 6 MeV has a range of 4.6 cm in the air and 56 μm in the human tissue. Being a densely ionizing species of radiation, it will deposit its energy very quickly after encountering a medium. In practice this means that it does not penetrate the skin or even reach the skin from its origin. The risks with alpha active materials rise when they are inhaled or ingested since then the alpha-particles are in direct interaction with vital cells. To set an example, a 4 MeV alpha-particle causes approximately 23 000 ionizations, which means the dose for that tissue are is roughly 370 mGy [16].

Beta-particles are less energetic than alpha-radiation [10]. The electrons (or positrons) collide with electrons in the medium and hence have similar behavior in human tissue than alpha-particles. As a scale, 1 MeV beta-particle has range of 0.5 cm in human tissue, and ^{137}Cs emits beta-particles with an average energy of 0.2 MeV. If these β-particles emitted by ^{137}Cs hit the skin, it will not be penetrated through it, but will cause burn injuries if the skin is exposed to significant amount of radiation. This cesium isotope is relevant when NPP accidents are considered (see chapter 3). Gamma radiation penetrates the skin deeper than alpha and beta radiation. Gamma-rays can penetrate soft tissue and concrete. Another way to demonstrate its pervasive properties is so called *half-value layer*, which for water is 9 cm. This means that 50 % of gamma quanta emitted by ^{137}Cs, with energy of 0.662 MeV, penetrates a 9 cm layer of water [10]. The fig. 2.4 shows the schematics of radiation penetration for alpha, beta, and gamma radiation.

2.3.1 Deterministic and stochastic effects

The effects of ionizing radiation can be divided in two categories: *deterministic* and *stochastic effects* of radiation. The deterministic effects occur when a person is exposed to a large dose of radiation and the effects are inevitable when a certain dose threshold is exceeded. Deterministic effects originate from vast damaging of the cells. Large doses are related usually to radiation treatment or a severe nuclear accident.

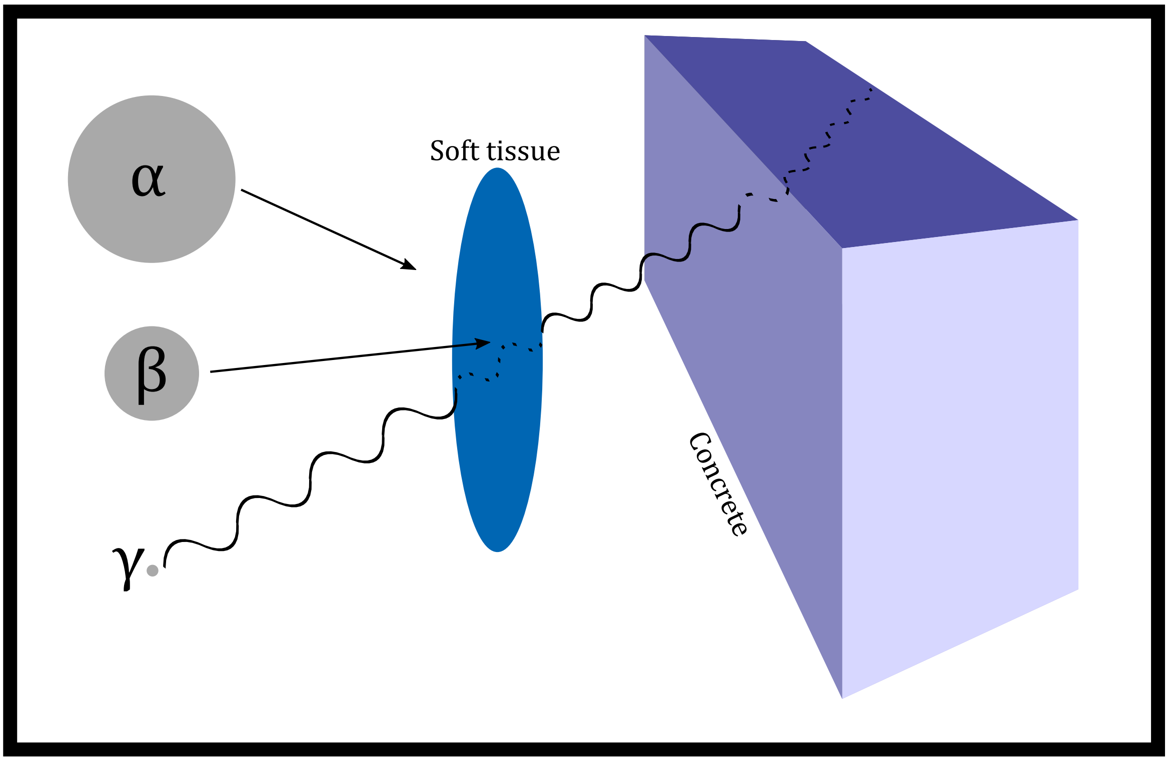

FIGURE 2.4: Penetration capability schematics for different types of radiation. Illustration motivated by [10].

These deterministic effects are – for example – radiation sickness with damages in bone marrow and intestines, radiation burn, and fetal damage [15]. The threshold value for damage and damage rate depend highly on dose rate: if the large dose is spread to a long period of time the threshold value is lower and damages are less severe. Protecting individuals from deterministic effects is a corner stone of radiation protection.

Stochastic effects are statistical injurious effects that are caused by a random genetic change in a cell [15]. Statistical effects can originate from any small radiation exposure. There are no threshold values for these effects, but the probability of them increase when the dose increases. The most significant factor is the cumulative dose through life-time. Stochastic effects are not significant to a single individual but for the population the effects can be remarkable if a large number of people have been exposed.

Not all deterministic effects are immediate. They can also appear or alter for worse through time. However, the stochastic effects require a latent phase of at least few years.

Chapter 3

Radioactive materials in fission reactors and dispersion of the particles released from a nuclear power plant

This chapter introduces which radioactive materials are included in the conventional large light water nuclear reactors. The uranium used as the fuel of the nuclear reactor is radioactive, but the reaction products of the fission reaction are highly radioactive as well. To understand the radioactivity of the nuclear fuel and its fission products, we first discussed radioactive decay in general in section 2.1. How the fission reactions happen and lead to radiating nuclei is introduced in section 3.1

Section 3.2 introduces briefly the studied Finnish NPPs and section 3.3 covers the basics of nuclear power plant accidents. In section 3.4 we discuss the dispersion and deposition of radioactive materials.

3.1 Fission reactions

In fission reaction a heavy nucleus decays into two daughter nuclei [17]. Typically two or three neutrons are emitted in the process as well as gamma and neutrino radiation. Nuclei in which fission reaction can occur are called *fissionable*. If a low-energy neutron, usually referred as *thermal neutron*, can induce a fission reaction in a nucleus, it is called a *fissile* nucleus. A common neutron-induced fission reaction is [18]:

$$^{235}\mathrm{U} + \mathrm{n} \quad \longrightarrow \quad ^{93}\mathrm{Rb} + {}^{141}\mathrm{Cs} + 2\mathrm{n}.$$

Furthermore, the radioactivity yields from the fission products which are radioactive as well, usually they emit β and γ radiation. Two examples of fission product decay chains are below [18]:

$$\begin{array}{ccccccccc} ^{93}\mathrm{Rb} & \xrightarrow{6\ \mathrm{s}} & ^{93}\mathrm{Sr} & \xrightarrow{7\ \mathrm{min}} & ^{93}\mathrm{Y} & \xrightarrow{10\ \mathrm{h}} & ^{93}\mathrm{Zr} & \xrightarrow{10^6\ \mathrm{y}} & ^{93}\mathrm{Nb} \\ ^{141}\mathrm{Cs} & \xrightarrow{25\ \mathrm{s}} & ^{141}\mathrm{Ba} & \xrightarrow{18\ \mathrm{min}} & ^{141}\mathrm{La} & \xrightarrow{4\ \mathrm{h}} & ^{141}\mathrm{Ce} & \xrightarrow{33\ \mathrm{d}} & ^{141}\mathrm{Pr} \end{array}$$

3.1.1 Relevant fission products in a release

There are a number of fission products released in a nuclear accident. Within the scope of this thesis, three particular isotopes, iodine-131, cesium-134, and cesium-137, are given a special attention. Other nuclei modelled in the thesis are listed in chapter 6. Iodine and cesium are significant because of their radioactive properties. Radioactive iodine-131 is a β^- emitting isotope which clusters into thyroid and later on in the decay chain, it emits a gamma quantum [14]. Iodine-131 has half-life of circa 8 days [19]. Cesium isotopes are strong gamma emitters through beta-decay. Cesium-137 has a long half-life of approximately 30 years and the half-life of cesium-134 is circa 2 years, hence their deposition after NPP accident is meaningful for protective action planning [19]. The protective actions during an nuclear accident are discussed in more detail in chapter 4.

Radioactive iodine and cesium isotopes are solid in room temperature. In the high temperature circumstances of a nuclear reactor they are gasified, which make their release from the fuel more possible [17]. They can form radioactive particles e.g. via condensation and hence cause a significant radiological risk for people and the environment [20].

3.2 Finnish nuclear power plants

In this thesis the operational Finnish nuclear power plants are studied. Currently there are two operational NPP sites in Finland at Loviisa and Olkiluoto. Loviisa has two pressurized light water VVER-440 reactor units and Olkiluoto has two boiling water reactor units [21, 22]. Table 3.1 collects the basic information of these NPPs.

Fuel inventories used in this thesis are retrieved from STUK's database containing the information of current reactor inventory. Release scenarios are discussed in more detail in chapter 6. More information on the fuel inventories before current power upgrades are found in reference [6].

TABLE 3.1: Power information of the Finnish operational NPP-units [21, 22].

NPP unit	Reactor type	Thermal power (MW)	Electrical power (MW)
Loviisa 1&2	PWR	1500	507
Olkiluoto 1&2	BWR	2500	890

3.3 Nuclear power plant accidents

Nuclear power plant accidents can occur from many initial events. A release happens when the integrity of the nuclear fuel element and containment building are compromised, and the safety systems do not work properly. In such case fission products can leave the fuel element, leak into containment building, and be released to the environment through the damaged containment building. The fuel damage is caused by elevated temperature. The rise of the temperature can be caused for example in a case of a loss of coolant accident (LOCA) [17]. LOCA in pressurized water reactor, like in Loviisa, means that primary circuit is damaged and the coolant leaks into the containment building and the reactor core is exposed. In boiling water reactor similar scenario would be breaking of the main steam line.

After the core is exposed the fuel temperature rises and causes damage and leak of radioactive material into the containment building. At this point the integrity of the containment building becomes crucial. The scenarios studied in this thesis are based on different integrity levels of the containment building and how large a portion of the release is stopped by the containment building, which has the purpose of delaying the release into the environment. Chapter 6 introduces these scenarios in more detail. For further detail on accidents, the book *Ydinturvallisuus* published by STUK summarizes the basics of different accident categories [17].

3.4 Dispersion and deposition of radioactive materials

Dispersion of the radioactive material depends roughly on three circumstantial aspects: contents of the release, height of the release, and weather conditions. Contents in this case means both the isotope distribution and the state of the material. Materials can be released as solid particles, gas, or aerosols [14]. Supersaturated steam forms particles and particles can coagulate and form larger particles, which affect the dispersion. Radioactive particles decay through time, which changes the compositions of the release cloud.

The key weather conditions are wind and vertical temperature profile. Wind determines the horizontal direction and temperature differences create pressure gradients affecting the vertical dispersion. Aerosol particles are modelled in general with Brownian motion and diffusion [14]. The size of the particles is related to the distance of dispersion. Larger particles are more affected by the gravity than the smaller ones. Large particles therefore are deposited faster, i.e. within shorter distance from the source, than the smaller particles.

At the end of the airborne dispersion, the radioactive particles fall-out on the surface of the ground via *wet* and *dry deposition* [14]. The scope of this thesis does not cover deposition to the marine area or lakes.

In the dry deposition the particles drift near ground surface and stick to it [14]. Rainfall, fog, and snow cause the wet deposition. The particles dissolve to water and therefore the wet deposition is much more efficient than the dry deposition.

The dispersion and deposition models used in this study are discussed in more detail in chapter 5. The cited book *Säteily ympäristössä*, published by STUK, offers a broader general description of dispersion and deposition [14].

Chapter 4

Emergency preparedness and protective actions during a nuclear power plant accident

This chapter presents the Finnish means to prepare for a radiological nuclear power plant accident and the protective actions during such emergency event. The guidelines for the *protective actions* are stated in the emergency preparedness guides (VAL-guides) 1 & 2 [23, 24]. *A nuclear or radiological emergency* is divided into *early*, *intermediate*, and *recovery phases* [25]. This thesis studies early and intermediate phase related quantities. The contents of VAL-guides are discussed in more detail in section 4.2. Later on, protective actions in this thesis refer specifically to actions taken during a nuclear emergency.

A nuclear or radiological emergency is a situation when there is a threat of an event or an event has occurred, which lead to public's and/or rescue and protective personnel's exposure to higher amount radiation than normally [23].

In section 4.1 the emergency planning zones of the Finnish nuclear power are briefly introduced. If an NPP accident should occur VAL-guides dictate the proper actions for protecting the population. Section 4.2 discusses these protective actions and how their need during an emergency is defined.

4.1 Emergency planning zones of the nuclear power plants

In Finland, STUK's regulation STUK Y/2/2018 orders a nuclear power plant to have *precautionary action zone* (PAZ), which is an are with radius of circa 5 km from the site [26]. The PAZ has limitations in land use. The same regulation defines an area with circa 20 km radius from the NPP site, which is called *emergency planning zone* (EPZ). Inside the EPZ, the authorities must make an external rescue plan referred in Rescue Act (379/2011) section 48(1)(1) [3].

The EPZ and PAZ for a imaginary NPP are illustrated in figure 4.1. It must be noted, that in practice the zones are defined with respect to municipality and city borders, not with exact circles.

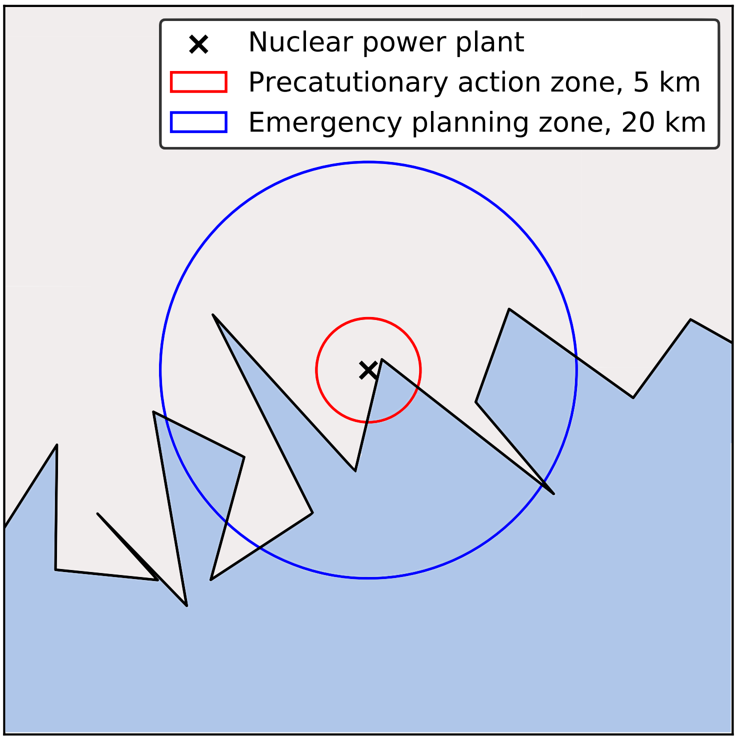

FIGURE 4.1: Schematics of Finnish NPP site emergency planning zones.

4.2 Protective actions during a nuclear power plant accident

Purpose and reasoning of protective actions

The VAL-guides state that the goal of any protective actions is to keep the population's radiation dose exposure as low as reasonably and practically possible. Another goal is to minimize any other disadvantages for society and to help normalizing the living conditions and functions of the society [23].

Reference level of dose

In Finland the primary *reference level of dose* is set to 20 mSv [23]. This level guides the protective actions to keep the residual dose of an individual under that level during the first year after the initial event. The reference level should be re-evaluated during the event. The level should be lowered in time until a permanently acceptable level is reached.

Dose criteria of the protective actions and operational intervention levels

The basis of each protective action is a certain *dose criteria*, which should not be exceeded [23]. A protective action should take place if its dose criterion is estimated to be exceeded. From these criteria are derived the *operational intervention levels (OILs)*, which can be measured during the emergency. OILs are given as external radiation dose rates (μSv/h), deposition (Bq/m^2), and air activity concentration (Bq/m^3). The numerical values of these criteria and intervention levels are introduced on the section 4.2.1 along the relevant protective actions.

Since dose estimation includes significant uncertainties, OILs and dose criteria are not strict values but to be used as guidance and in magnitude evaluation. These values are given for the most exposed population group and for an *unprotected person*. An unprotected person has not sheltered inside, been evacuated, or received iodine prophylaxis [25].

VAL-guide 1 lists situations when protective actions are justified with respect to the reference level of dose. Protective actions are justified, if the annual dose following the accident is estimated to be [23]:

- over 10 mSv: actions to reduce exposure to be taken
- 1-10 mSv: protective actions are usually justified
- less than 1 mSv: actions to reduce can be taken if they are easily and reasonably executable.

If a dose of 100 mSv is expected to be exceeded in a short period of time (approximately 24 hours), protective actions are unconditionally necessary and to be executed urgently.

Contamination levels

Contamination levels describe the magnitude of the fallout [23]. They are primarily defined based on the external dose rate from deposited radio nuclides. Contamination levels assist in the decontamination processes, which are not studied within the scope of this thesis, but it is helpful to familiarize oneself with these levels, since deposition quantities are studied.

4.2.1 Protective actions

This section introduces considerable protective actions including the dose criteria and operational intervention levels related to them. All descriptions are based on VAL-guides, unless otherwise cited. Summary of the dose criteria and operational intervention levels for early phase of an emergency is in table 4.2 and for intermediate phase in the table 4.3.

Sheltering indoors and partial sheltering indoors

Sheltering indoors reduces the exposure to airborne radioactive particles and decreases the dose caused by external radiation. Sheltering should take place well before the radioactive cloud passes the area. This means the order ought to be given 4 hours in advance or as soon as possible if it is not possible to give this order within this time frame. To prevent the radioactive particles from ending up indoors, should the air condition of all possible buildings be turned off. Doors, windows, chimneys and other airways should be sealed.

Sheltering should not last more than 48 hours, since other disadvantages related to everyday life increase quickly when being sheltered for a long period of time. Also,

TABLE 4.1: Contamination levels [24]

Contamination level	External dose rate	Combined γ- and β-emitter deposition	α-emitter deposition capable to sever from the ground
Extremely contaminated	over 100 μSv/h	over 10 MBq/m^2	over 100 kBq/m^2
Heavily contaminated	10-100 μSv/h	1-10 MBq/m^2	10-100 kBq/m^2
Contaminated	1-10 μSv/h	100 - 1000 kBq/m^2	1-10 kBq/m^2
Slightly contaminated	less than 1 μSv/h yet over normal background radiation	less than 100 kBq/m^2	less than 1 kBq/m^2
Non-contaminated	Dose rate in the level of normal background radiation	no contamination or very low contamination	no contamination or very low contamination

the indoors contamination is inevitable after 48 hours in the area of the influence of the radioactive cloud, regardless of window sealing and turning off the air condition.

Less invasive protective action is partial sheltering. It is recommended in situations when there are radioactive particles in the air and environment, but the sheltering is not necessary. In partial sheltering one should avoid unnecessary staying outdoors.

Only in case of nuclear explosion it is necessary to shelter into air-raid shelters. This corresponds to estimated dose of 100 mSv in 24 hours. This scenario is out of the scope of this thesis.

In early phase dose criterion for sheltering is that 10 mSv dose is predicted to be exceeded during the next 48 hours. Significant operational intervention levels are when dose rate exceedes or it is predicted to be over 100 μSv/h or when airborne strong gamma emitter concentration exceeds 10 kBq/m^3. Other OILs are with respect to sheltering are listed in table 4.2. Partial sheltering has similar operational intervention level, but with smaller order of magnitude. Dose criterion being 1-10 mSv during 48 hours, dose rate being 10 μSv/h, and gamma emitter air concentration 1 kBq/m^3. Other OILs are listed in the table 4.2.

In the intermediate phase, the dose criterion and dose rate OIL for sheltering are the same as in the early phase. For partial sheltering, dose criterion is 10 mSv exposure during the first month but under 10 mSv during 48 hours. Dose rate OIL for partial sheltering is 10-100 μSv/h. In the intermediate phase the total activity is no more changing and all the radioactive material is deposited. Considering strong gamma emitter deposition, operational intervention level to start or continue sheltering is 10 MBq/m^2. For partial sheltering this value is 1-10 MBq/m^2. Other OILs are found in table 4.3.

Iodine prophylaxis

As mentioned in section 3.1.1 the radioactive iodine can be released in NPP accident and therefore can end up inside human body via inhalation, via food, water and milk, or externally when handling contaminated surfaces. With the intake of stable iodine, one can prevent the radioactive iodine from accruing into thyroid during early phase of emergency. It does not reduce dose to other organs.

Iodine prophylaxis is very important to children and the pregnant. The thyroids of children and fetuses are more sensitive to radiation effects. The dose criterion for iodine prophylaxis is a thyroid dose of 100 mGy for adults and thyroid dose of 10 mGy for children and the pregnant. Corresponding OILs for adults are 100 μSv/h dose rate or radioactive iodine air concentration greater than 10 kBq/m^3. For children and the pregnant, these OILs are 10 μSv/h and 1 kBq/m^3.

One should not exit indoors to purchase iodine tablets if sheltering indoors is already ordered. Iodine prophylaxis is always a complementary action to sheltering indoors. The iodine should be taken in 1-6 hours before exposure to radioactive iodine to maximize its benefits. One should not take stable iodine 12 hours after the inhalation of radioactive iodine, since the stable iodine slows down the radioactive iodine from leaving the thyroid.

Evacuation, relocation and access control

In case of a nuclear emergency and its early phase, if a severe accident is anticipated the population in precautionary action zone is evacuated and iodine prophylaxis is ordered to them. Otherwise, evacuation should be considered if the release is estimated to last over 48 hours and/or sheltering need is over hours. Access control actions are in order to those areas evacuated or where sheltering indoors is ordered.

In the intermediate phase, there can be a short term evacuation in the contaminated areas when the first week dose is estimated to be 20 mSv or over. Operational intervention levels exceeding for more than 48 hours are dose rate of 100 μSv/h and strong gamma emitter deposition of 10 MBq/m^2. Other OILs are listed in table 4.3. If dose is estimated to be over 10 mSv during one month, temporary relocation can be considered. OILs related to relocation are in table 4.3. Access control in the intermediate phase is in order in the areas where evacuation or sheltering is ordered.

TABLE 4.2: Dose criterion and the directive operational intervention levels related to them in the early phase of an emergency.

EARLY PHASE

Protective action	*Dose criterion* and/or operational intervention level
Sheltering indoors	• *Dose ≥ 10 mSv in 48 hours.* • External dose rate is or is predicted to be > 100 μSv/h, or • α-emitter concentration > 1 Bq/m^3 (Pu-239, Am-241), or • β-emitter concentration > 1 kBq/m^3 (Sr-90), or • Strong γ-emitter concentration in total > 10 kBq/m^3 (Cs-137, I-131, etc.)
Partial sheltering indoors	• *Dose: 1-10 mSv in 48 hours.* • External dose rate is, or is predicted to be, > 10 μSv/h, or • α-emitter concentration > 0.1 Bq/m^3 (Pu-239, Am-241), or • β-emitter concentration > 100 Bq/m^3 (Sr-90), or • Strong γ-emitter concentration in total > 1 kBq/m^3 (Cs-137, I-131, etc.)
Iodine prophylaxis (adults)	• *Thyroid dose over 100 mGy.* • External dose rate is or is predicted to be > 100 μSv/h, or • Air concentration of radioactive iodine during 48 hours is or is predicted to be > 10 kBq/m^3
Iodine prophylaxis (children and the pregnant)	• *Thyroid dose over 10 mGy.* • External dose rate is or is predicted to be > 10 μSv/h, or • Air concentration of radioactive iodine during 48 hours is or is predicted to be > 1 kBq/m^3
Evacuation	• *Dose during first week after accident is predicted to be > 20 mSv.* • It is likely that the need of sheltering indoors is more than 48 hours
Access control	• External dose rate is or is predicted to be > 100 μSv/h, or • α-emitter concentration > 1 Bq/m^3 (Pu-239, Am-241), or • β-emitter concentration > 1 kBq/m^3 (Sr-90), or • Strong γ-emitter concentration in total > 10 kBq/m^3 (Cs-137, I-131, etc.), or • Areas where sheltering or evacuation is ordered.

TABLE 4.3: Dose criterion and the directive operational intervention levels related to them in the intermediate phase of an emergency.

INTERMEDIATE PHASE

Protective action	***Dose criterion* and/or operational intervention level**
Sheltering indoors	• *Dose ≥ 10 mSv in 48 hours.* • External dose rate is or is predicted to be > 100 μSv/h, or • Strong γ- and β-emitter deposition in total > 10 MBq/m^2 (Cs-137, I-131, Sr-90 etc.), or • α-emitter deposition is > 100 kBq/m^2 (Pu-239, Am-241) assuming the emitters are able to leave ground surface
Partial sheltering indoors	• *Dose ≥ 10 mSv in two months but < 10 mSv in 48 hours.* • External dose rate is, or is predicted to be, > 10 μSv/h, but < 100 μSv/h, or • Strong γ- and β-emitter deposition in total is 1-10 MBq/m^2 (Cs-137, I-131, Sr-90 etc.), or • α-emitter deposition is 10-100 kBq/m^2 (Pu-239, Am-241) assuming the emitters are able to leave ground surface
Evacuation	• *Dose during first week after accident is predicted to be > 20 mSv* • External dose rate is, or is predicted to be, > 10 μSv/h, or • Strong γ- and β-emitter deposition in total > 10 MBq/m^3 (Cs-137, I-131, Sr-90 etc.), or • α-emitter deposition is > 100 kBq/m^2 (Pu-239, Am-241) assuming the emitters are able to leave ground surface, or • It is likely that the need of sheltering indoors is more than 48 hours
Relocation	• *Dose during first month after accident is predicted to be > 10 mSv* • External dose rate is, or is predicted to be, > 10 μSv/h regardless of decontamination, or • Strong γ- and β-emitter deposition in total > 1 MBq/m^3 (Cs-137, I-131, Sr-90 etc.) regardless of decontamination, or • α-emitter deposition is > 10 kBq/m^2 (Pu-239, Am-241) assuming the emitters are able to leave ground surface regardless of decontamination, or
Access control	• Areas where sheltering or evacuation is ordered.

Chapter 5

Modeling airborne dispersion of radioactive release and doses to the population

This chapter introduces the calculation process used in the thesis. Firstly, we discuss the weather data used in calculations in section 5.1. Section 5.2 covers the calculations considering the dispersion of the radioactive release and the deposition calculations related to these releases. The dispersion and deposition calculations are made with dispersion model *SILAM* developed by the Finnish Meteorological Institute (FMI) [27]. Dose calculations are done with STUK's threat assessment tool TIUKU based on SILAM results. The fundamentals of these dose calculations are introduced in section 5.4.3.

The overall calculation process is illustrated in fig.5.1. The post processing methods of the data is discussed more in chapter 7.

5.1 Weather data

The weather data for the calculations used in the purposes of this thesis was collected by Finnish Meteorogical Institute (FMI) [28]. Data covers operative weather forecasts from years 2012-2015. The weather models used at FMI are AROME and HARMONIE [29]. In the years 2012-2013 AROME was used whereas HARMONIE was used in 2014-2015. The data comprehensiveness percentage for each studied year is given in table in table 5.1.

TABLE 5.1: Coverage percentage of the weather data for each year [28].

Year	Coverage percentage (%)
2012	95
2013	100
2014	98
2015	98

To determine the representativeness of the weather conditions of the studied time period they were compared to the climatic comparison period of 1981-2010 [28]. The

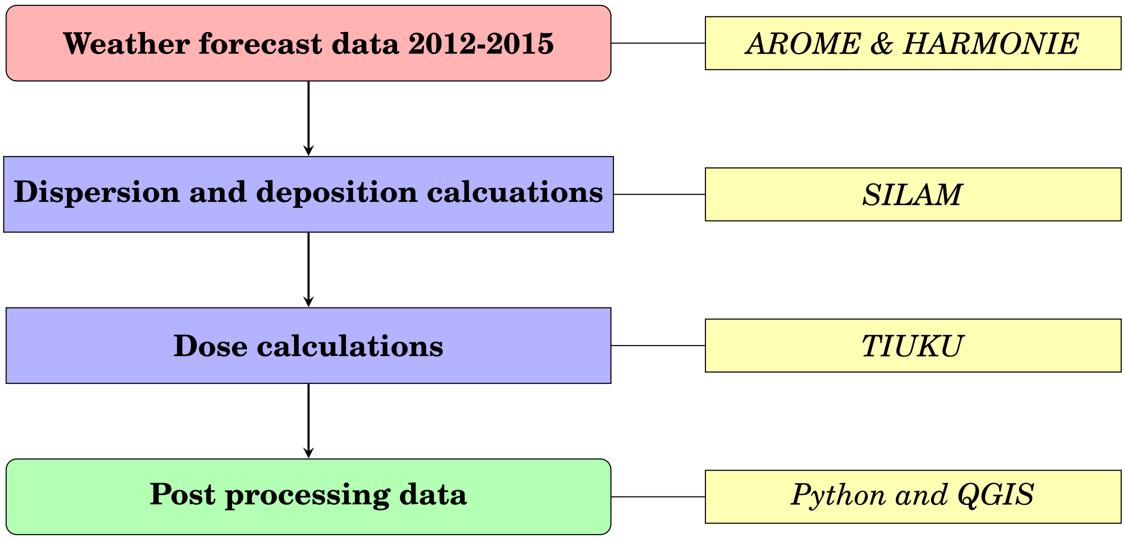

FIGURE 5.1: The calculation process.

analysis showed that the most significant characteristic of the time period 2012-2015 was the exceptional high average temperature of the years 2013-2015. The high temperatures took place in the summer in 2013 and in the winter during 2014 and 2015.

5.2 Dispersion and deposition calculations using SILAM

The disperision and deposition calculations are done using SILAM – a global-to-meso-scale dispersion model – based on weather data discussed in sec. 5.1. SILAM is an acronym for System for Integrated modeLing of Atmospheric coMposition. The development process of SILAM is continuous and, for the purposes of this thesis, SILAM version 5.4 was used.

SILAM model includes both Eulerian and Lagrangian transport methods [30]. The data produced for this analysis was done using Eulerian method. It is based on a dispersion equation which takes into account the concentration of the radioactive material, source term, coordinates of the particles, transport velocity, turbulent diffusion, air density, and transformation and sink processes. For more thorough description see [31].

5.3 Modeling parameters

In all cases the calculation grids were set to 300 km radius from the nuclear power plant site [28]. The AROME model set some restrictions since it covers only Finland and none of the neighbouring countries. Using the Eulerian method, it was possible to use same grid for the weather modeling and dispersion calculations. However, the switch from AROME to HARMONIE caused a change in the grids. Therefore the results from the dispersion calculations were unified by interpolating them linearly. The final grid had a resolution of $0.02° \times 0.02°$ in longitude-latitude projection.

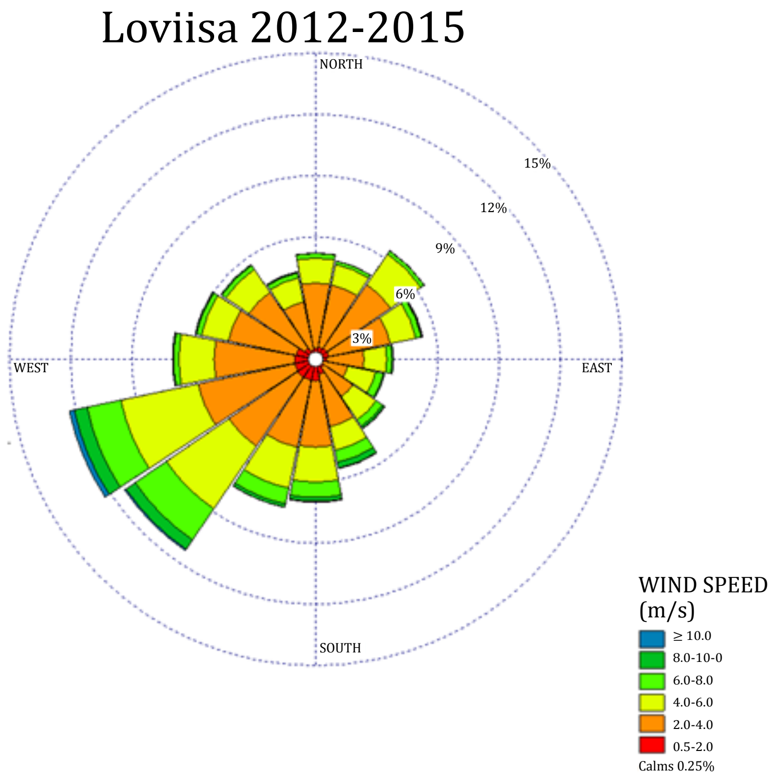

FIGURE 5.2: Wind rose of Loviisa in 2012-2015 [28].

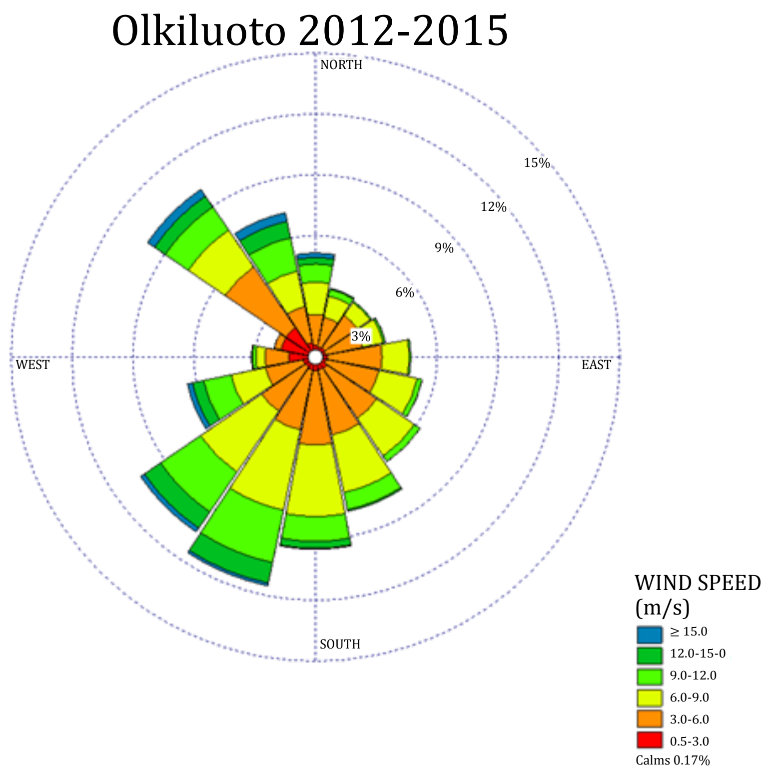

FIGURE 5.3: Wind rose of Olkiluoto in 2012-2015 [28].

Vertically the calculations were done in 16 layers, highest reaching 10 km from the ground surface. The layer thickness varied depending on the altitude. The lowest layer was 40 m thick, between 1-4 km 500 m, between 4-6 km 1000m, and 6-10 km 2000 m.

For each case, the time step was 2 minutes and the calculations were executed for time period of 48 hours after the release. There were two sets of releases considering different nuclides. One release was 3 hours and the other was 12 hours. These releases were set to begin at 00 UTC and 12 UTC for each day during the 2012-2015 period. More details about the release scenarios is in chapter 6. Naturally the power plant sites were the starting point of each scenario: Loviisa (26.342° E, 60.372° N) and Olkiluoto (21.444° E, 61.235° N). The releases were modeled as point-like release in the altitude of 90-110 m.

Each release consisted of the noble gases chromium-88, chromium-88, xenon-133, and xenon-135. Iodine-131 was modelled in forms of gas and aerosol. Other aerosol nuclei were: strontium-89, strontium-90, tellurium-127m, cesium-134, and cesium-137. The used source terms are introduced in more detail in chapter 6. The aerosols in the model had average diameter of 0.6 μm.

5.4 Radioactive decay, deposition and dose calculations in the model

5.4.1 Decay

SILAM model calculates radioactive decay of the released nuclei from air and deposition activity. The Eulerian model calculates the decay for every time step for each grid point. The simulations consider the daughter nuclei from the following decay chains:

^{87}Kr	→	^{87}Rb	^{88}Kr	→	^{88}Rb	^{135}Xe	→	^{135}Cs
^{131}I	→	^{131m}Xe	^{90}Sr	→	^{90}Y	^{127m}Te	→	^{127}Te
^{137}Cs	→	^{137m}Ba	^{241}Pu	→	^{237}U	^{241}Am	→	^{241}Pu

Considering other simulated nuclei, the decay is taken into account but the decay products are neglected.

5.4.2 Deposition

The deposition of the SILAM model is based on dry and wet deposition [28]. The dry deposition is based on the deposition velocity of the particles, v_d. Dry deposition flux F [Bqm^{-2}s^{-1}] can be expressed with this velocity as [32]:

$$F = -v_\mathrm{d} c(z_\mathrm{ref}), \tag{5.1}$$

where $c(z_\mathrm{ref})$ is the activity concentration on the lowest calculation surface above the point of deposition. SILAM uses the following estimate for the deposition velocity

[32, 33]:

$$v_\mathrm{d} = \frac{1}{r_\mathrm{a} + r_\mathrm{b} + r_\mathrm{a} r_\mathrm{b} v_\mathrm{s}} + v_\mathrm{s}, \tag{5.2}$$

where r_a is aerodynamic resistance, r_b is quasi-laminar layer resistance, and v_s is settling velocity which is assumed to be constant.

SILAM models the particle reduction caused by wet deposition point-wise with the dime derivative of air activity concentration such that [34]:

$$\frac{\mathrm{d}c}{\mathrm{d}t} = -\Lambda c, \tag{5.3}$$

where c is activity concentration of air and Λ is scavenging coefficient or so called washout coefficient. Λ describes the rate of loss of gases or aerosol particles from atmosphere via rain or snow. The cumulative wet deposition is calculated by summing up the particle reduction in the grid points above the deposition point. The three dimensional distribution of the scavenging coefficient is defined from total rainfall of HARMONIE and AROME weather data.

5.4.3 Dose calculation method

STUK's threat assesment tool TIUKU calculates dose rates and doses from deposition and airborne activity concentration near the ground level [35]. Ground level is chosen as an approximation to make the calculation time more reasonable. The activity is divided into an even grid of point sources. Effective dose and thyroid dose for adults and one year old children are calculated in this study. Pathways are inhalation and external dose from radioactive cloud and fallout [36, 37]. The dose rate conversion factors are retrieved from the data base of JRODOS decisiono support system and calculated in accordance with the recommendations of the ICRP-119 document [38, 39]. Dose calculations are made on two time integration intervals: first 48 hours after release and first 7 days after release.

Chapter 6

Accident scenarios and source terms

In this thesis the accident scenarios are studied for two sites and for two reactor types: Loviisa 1 & 2 and Olkiluoto 1 &2. The scenarios are divided to three different cases. These cases are evaluations to estimate a small release (later *basic case*), a large release (later *large case*), and a very large release (later *very large case*). They are described in more detail below and the source terms are summarized in tables 6.1 and 6.2. Each release case is based on a certain fixed source term parameters, which then are scaled according to reactor inventory. Inventory is related to the power of the reactor.

The purpose of these different cases is to create estimates for the need of protective actions. Hence, these source term values are somewhat gross, since the precise inventories and all of the initial circumstances of an accident are unique for each reactor and for each real-life case. The assumption in all scenarios is that the reactor has been shutdown in some way. Thereby the fission chain reaction has ended and the problems are caused by the decay heat.

Basic case

The basic case estimates a case that the containment building of the reactor is not completely impermeable anymore. The release from the containment starts six hours after the fission chain reaction has ended. The release of ^{137}Cs, ^{134}Cs, and ^{131}I are fixed to 100 TBq. This release occurs through the first 3 hours. In the same time window 0.4 TBq of ^{89}Sr, ^{90}Sr isotopes are released and 40 TBq of ^{127m}Te. During the first 12 hours it is estimated that 2% of the ^{87}Kr, ^{88}Kr, ^{133}Xe, and ^{135}Xe inventories are released.

Large case

Large case release describes a situation where containment building is damaged quick after the end of the fission chain reaction. This time after shutdown has been set to one hour. The release to the environment from the damaged containment building is defined so that 1% from the ^{137}Cs, ^{134}Cs, and ^{131}I inventories of the reactor during the first three hours of the release. Through same time window are released 0.4% of the

^{127m}Te inventory and 0.004% of the ^{89}Sr, ^{90}Sr inventories. During the first 12 hours the release consists 20% of the ^{87}Kr, ^{88}Kr, ^{133}Xe, and ^{135}Xe inventories.

Very large case

The worst case studied is to estimate the consequences of a very large release. The case simulates a maintenance shutdown where the containment building is not secured and there are significant pathways for the release. The release starts 48 hours after the end of the chain reaction. During the first three hours the release is one magnitude higher than in the large case. This means 10% of the ^{137}Cs, ^{134}Cs, and ^{131}I inventories, 4% of the ^{127m}Te inventory, and 0.04% of the ^{89}Sr, ^{90}Sr inventories. During the first 12 hours the ^{87}Kr, ^{88}Kr, ^{133}Xe, and ^{135}Xe inventories are completely released.

TABLE 6.1: Loviisa 1&2 release scenarios.

LOVIISA 1&2			
Case	**Start of the release***	**Release during the first 3 h**	**Release during the first 12 h**
Basic	6 hours	– ^{137}Cs: 100 TBq – ^{134}Cs: 147 TBq – ^{131}I: 882 TBq – ^{89}Sr 3.2 TBq – ^{90}Sr: 0.3 TBq – ^{127m}Te: 53 TBq	– ^{87}Kr: 19 TBq – ^{88}Kr: 1000 TBq – ^{133}Xe: 58 000 TBq – ^{135}Xe: 22 000 TBq
Large	1 hour	– ^{137}Cs: 1600 TBq – ^{134}Cs: 2400 TBq – ^{131}I: 15 000 TBq – ^{89}Sr 52 TBq – ^{90}Sr: 4.7 TBq – ^{127m}Te: 850 TBq	– ^{87}Kr: 3000 TBq – ^{88}Kr: 34 200 TBq – ^{133}Xe: 584 000 TBq – ^{135}Xe: 226 000 TBq
Very Large	48 hours	– ^{137}Cs: 16 200 TBq – ^{134}Cs: 23 800 TBq – ^{131}I: 146 000 TBq – ^{89}Sr 520 TBq – ^{90}Sr: 47 TBq – ^{127m}Te: 8500 TBq	– ^{87}Kr: 25 600 TBq – ^{88}Kr: 219 000 TBq – ^{133}Xe: 2 920 000 TBq – ^{135}Xe: 1 110 000 TBq

**Hours after the end of the fission chain reaction.*

TABLE 6.2: Olkiluoto 1&2 release scenarios.

OLKILUOTO 1&2			
Case	**Start of the release***	**Release during the first 3 h**	**Release during the first 12 h**
Basic	6 hours	– ^{137}Cs: 100 TBq – ^{134}Cs: 109 TBq – ^{131}I: 1000 TBq – ^{89}Sr 4.4 TBq – ^{90}Sr: 0.3 TBq – ^{127m}Te: 5.6 TBq	– ^{87}Kr: 40 TBq – ^{88}Kr: 2000 TBq – ^{133}Xe: 102 000 TBq – ^{135}Xe: 42 000 TBq
Large	1 hour	– ^{137}Cs: 2400 TBq – ^{134}Cs: 2600 TBq – ^{131}I: 24 700 TBq – ^{89}Sr 105 TBq – ^{90}Sr: 7.2 TBq – ^{127m}Te: 134 TBq	– ^{87}Kr: 6000 TBq – ^{88}Kr: 70 000 TBq – ^{133}Xe: 1 029 000 TBq – ^{135}Xe: 454 000 TBq
Very Large	48 hours	– ^{137}Cs: 24 000 TBq – ^{134}Cs: 26 300 TBq – ^{131}I: 248 000 TBq – ^{89}Sr 1000 TBq – ^{90}Sr: 72 TBq – ^{127m}Te: 1340 TBq	– ^{87}Kr: 51 800 TBq – ^{88}Kr: 446 000 TBq – ^{133}Xe: 5 152 000 TBq – ^{135}Xe: 2 257 000 TBq

**Hours after the end of the fission chain reaction.*

Chapter 7

Post-processing methods

Post-processing of the dispersion and dose calculation data is done with *Python 2.7*. The SILAM model outputs `netCDF` files. These are processed with Python's `netCDF4` module [40]. The computational postprocessing is done with `NumPy` library for scientific computation and `csv` library is harnessed to convert the data to suitable format for map production [41, 42]. The map products are produced with geographic information system software *QGIS* version 2.18 and finalized with vector graphics software *InkScape* [43, 44]. All these software products are open source and freeware.

7.1 Choosing the studied weather scenarios from the data

Since the weather is rather hard to forecast and the four years of weather data contains also some extreme weather conditions. Therefore it is necessary to neglect some of the weather scenarios in order to do a sensible analysis. For the purposes of this thesis, it was chosen to use 95$^{\text{th}}$ percentile of the data. A simplified explanation of this is that 5% of the most extreme weather conditions, e.g. storms, are ruled out of the analysis. For an extended explanation, percentile means that if a certain value x_p of all possible values X corresponds to percentile p there are $p\%$ of values which are equal to this particular value or less [45]. This can be demonstrated with a probability P with respect to some general distribution function F (which in our case would correspond to weather scenarios):

$$P(X < x_p) = \int_{-\infty}^{x_p} F(x) = 1 - p/100.$$

Being an analysis of potential consequnces in NPP accidents, not an thorough review of the emergency planning zones (see SSM's review [7]), it is justified to consider as much as 95% of the weather scenarios. In the SSM's review 70$^{\text{th}}$-90$^{\text{th}}$ percentiles were used.

The percentiles were calculated from the dispersion and dose data with `percentile` function in the `NumPy` library. When the desired amount of cases were processed the data was converted to comma-separated values with functions from Python's `csv` library.

Chapter 8

The results of the dispersion modeling and discussion

This chapter consists of the results from the dispersion and dose calculations. The activity concentrations in the air are discussed in sec. 8.1. Section 8.2 introduces selected results considering deposition. In section 8.3 the results considering doses and dose rates – linked to operational intervention levels – are shown. In this study thyroid dose and combined inhalation and external dose are calculated. Doses are defined for adults and one year old children.

The map products shown in this thesis are based on 95 percentile data of years 2012-2015. They show which consequences are possible in which locations in all calculated weather scenarios, not in a single release scenario. This way an assessment can be made whether the current PAZ and EPZ are valid or not. To set an example: compare two single scenarios of cesium deposition in figure 8.1 to those results from the whole data shown in section 8.2.

The last section of this chapter, sec. 8.5, covers the comparison of the results, the dose criteria and the operational intervention levels of the VAL-guides.

8.1 Activity concentrations in the air

The duration when strong gamma emitter air concentration exceeds 10 kBq/m^3 in the very large case during the first 48 hours after release is shown for Loviisa in fig. 8.2 and for Olkiluoto in fig. 8.3. The maximum time period is 4-5 hours at both sites.

These figures show that it is possible for the observed gamma emitter concentration to reach 4-5 hour duration circa 150 km from Loviisa site at Lappeenranta and circa 200 km from Olkiluoto site at Seinäjoki.

8.2 Deposition

Considering the intermediate phase of a radiological emergency, it is useful to asses the extent of cesium deposition and strong gamma emitter deposition after 48 hours of the release. Section 8.2.1 introduces the possible deposition scenarios for cesium deposition for both sites and for all release cases. In section 8.2.2 the equivalent examination is done for all studied strong gamma emitters, cesium isotopes included.

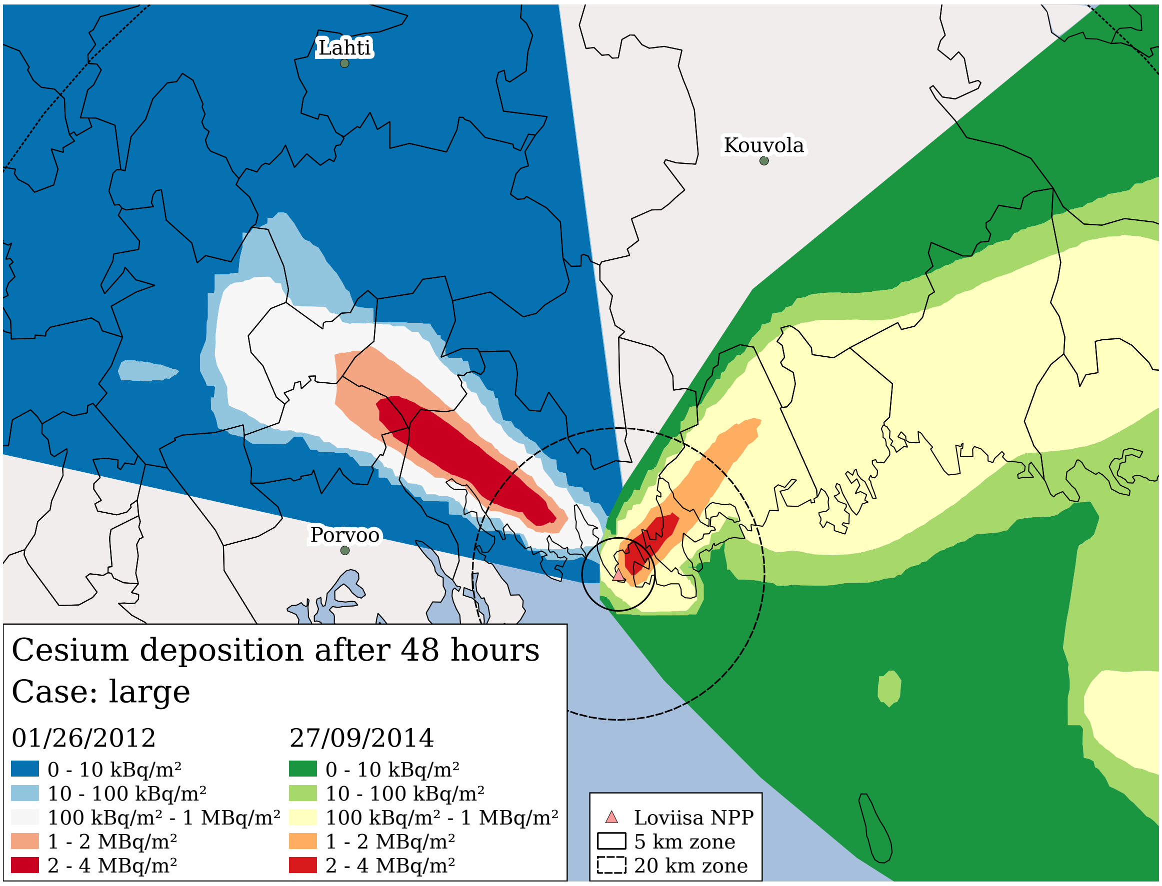

FIGURE 8.1: Combined ^{137}Cs and ^{134}Cs deposition after 48 hours in Loviisa large case for two single weather scenarios: Jan 26, 2012 and Sep 27, 2014.

8.2.1 Cesium deposition

Figures 8.4-8.8 show deposition for all Loviisa cases for combined ^{137}Cs and ^{134}Cs deposition after 48 hours. Similar cesium depositions for Olkiluoto cases are in figures 8.5-8.9.

The Loviisa (fig. 8.4) and Olkiluoto (fig. 8.5) basic cases show that for small release the prospected cesium depositions remain under 300 kBq/m^2. For Loviisa, the depositions in all scenarios do not reach the 20 km EPZ border. For Olkiluoto this EPZ border is exceeded for some weather scenarios with deposition under 50 kBq/m^2 but practically in every scenario the deposition over 100 kBq/m^2 is within the 5 km UPZ.

For large cases the cesium depositions are presented in figure 8.6 for Loviisa and in figure 8.7 for Olkiluoto. For both sites the maximum deposition is circa 4 MBq/m^2 and it remains within the 5 km zone. Deposition over 1 MBq/m^2 does not exceed the emergency preparedness zone.

Figures 8.8 and 8.9 show the very large cases. The maximum depositions are circa 40 MBq/m^2 for both Loviisa and Olkiluoto. For the studied scenarios, the 10 MBq/m^2 deposition is likely to stay within the EPZ and the maximum values within UPZ at both sites.

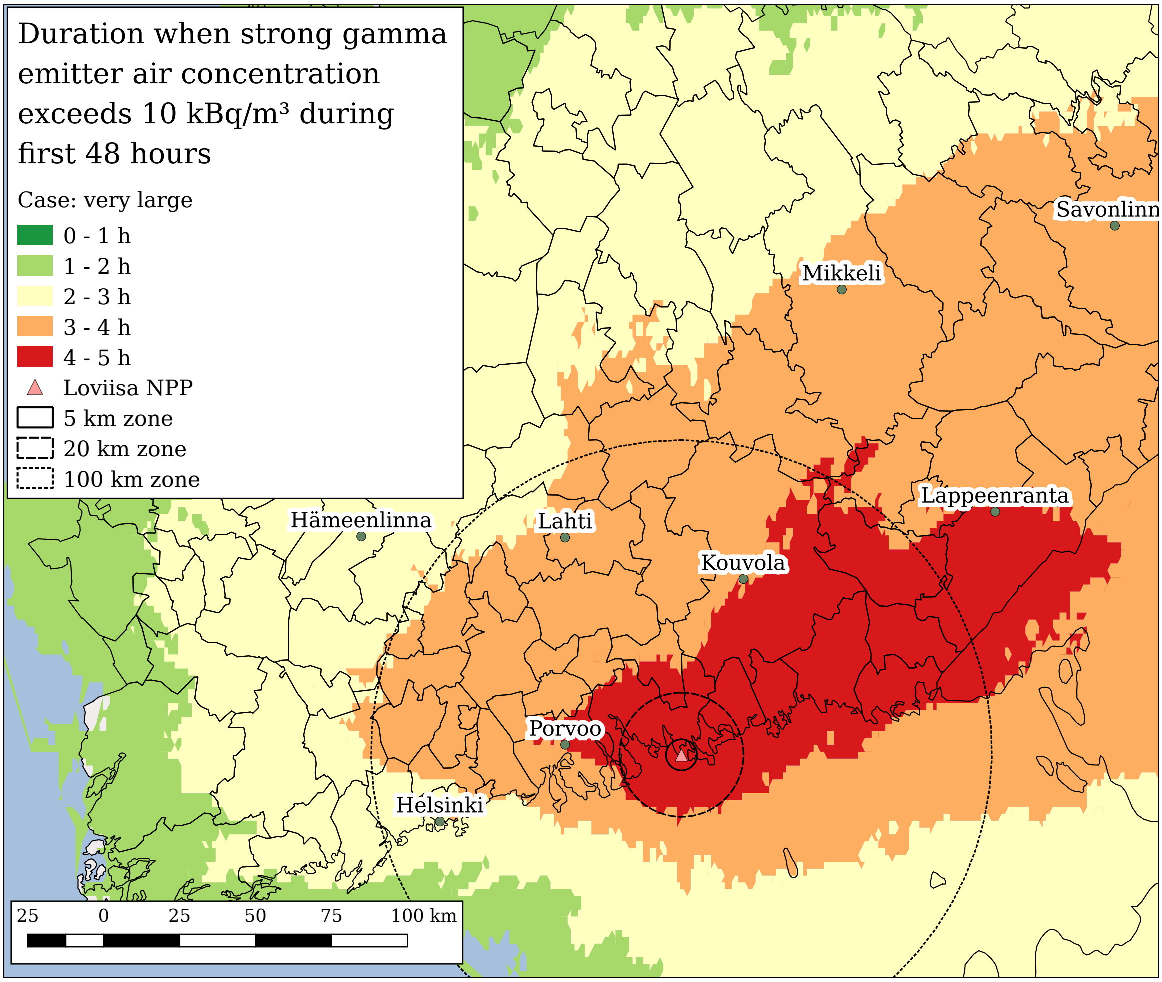

FIGURE 8.2: Time map of duration when gamma emitter air activity concentration 10 kBq/m^3 is exceeded in Loviisa very large case.

8.2.2 Strong gamma emitter deposition

Basic case gamma depostions are showed in figures 8.10 and 8.11. Gamma emitter deposition seems to have maximum values of circa 2 MBq/m^2 for both sites. The contribution of cesium is roughly 1/10 of the total depostion. 1 MBq/m^2 fallout is restricted within 20 km zone at Loviisa's case, for Olkiluoto there are some scenarios to exceed this distance with few kilometers.

Large case strong gamma emitter depositions are illustrated in figure 8.13 for Loviisa and in figure 8.13 for Olkiluoto. At the Loviisa site, the maximum value is circa 40 MBq/m^2 and at Olkiluoto it is circa 60 MBq/m^2. These large fallouts stay inside the 20 km zone, but the 10 MBq/m^2 deposition crosses the 20 km border in some weather conditions.

The very large release scenario would cause a significant gamma emitter deposition. Figures 8.14 and 8.15 show these depositions with maximum values of 400 MBq/m^2 for Loviisa and 580 MBq/m^2 for Olkiluoto site. Strong gamma emitter fallout of 10 MBq/m^2 reaches 100 km distance from the site in significantly many weather scenarios at both sites.

8.3 Dose rates and doses

8.3.1 Dose rates

The dose rate of interest is 100 μSv/h. Duration when this dose rate is exceeded during the first 48 hours is significant only in very large cases. Time map for duration is illustrated in fig. 8.16 for Loviisa and in fig. 8.17 for Olkiluoto. At the Loviisa case, the dose rate is over 100 μSv/h for the whole simulation period at the UPZ and outside of it, but outside the 20 km EPZ the duration stays under 6 hours. In Olkiluoto there are several scenarios where the 48 hour duration reaches the 20 km distance and even exceeds it with few kilometers in the direction of the city of Pori. Even though the 48 hour range is wide, otherwise the dose rate of 100 μSv/h is exceeded for 6 hours or less outside the EPZ.

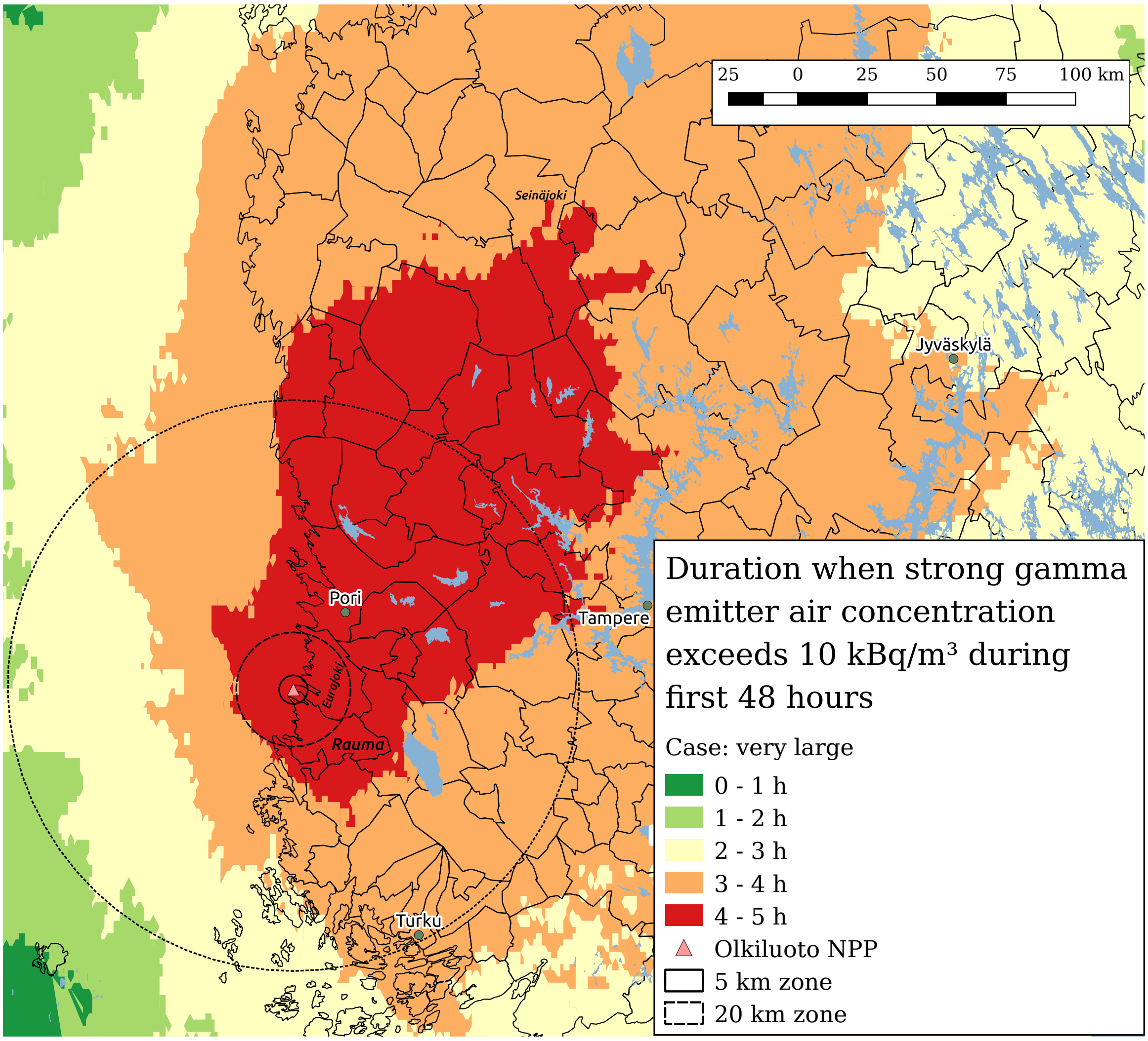

FIGURE 8.3: Time map of duration when gamma emitter air activity concentration 10 kBq/m^3 is exceeded in Olkiluoto very large case.

8.3.2 Doses

Dose calculations for 48 hour time integration interval were not significant in any of the scenarios. Hence, the following covers only the 7 day interval results.

External and inhalation pathway dose

In the large cases external dose combined with inhalation dose for unprotected adults during the first week are shown at Loviisa in fig. 8.18 and at Olkiluoto in fig. 8.19. For Loviisa the first week dose remains under 6 mSv and for most scenarios the 4 mSv threshold is not exceeded outside the emergency planning zone. For Olkiluoto the maximum values are higher – 7-9 mSv – in the precautionary action zone and outside of it at the coast. Outside the 20 km radius the doses can rise up to 5 mSv, but in the most cases the dose remains under 3 mSv.

For very large case the similar dose examination for unprotected adults during the first week is illustrated in figure 8.20 for Loviisa and in figure 8.21 for Olkiluoto. The results show that at the Loviisa PAZ the doses can reach 60 mSv and when reaching the 20 km zone border the doses stay under 30 mSv for most scenarios. In some scenarios the dose between 10-20 mSv can be exceeded in Kotka. At Olkiluoto the doses are higher: maximum values at 80-90 mSv inside the PAZ. Between 5-20 km radii the doses reach 40-60 mSv in most cases but outside EPZ the doses remain between 20-40 mSv. 10 mSv can be exceeded at Rauma and eastern Pori.

Dose calculations for unprotected children during the first week in large cases are shown in figure 8.22 for Loviisa and in figure 8.23 for Olkiluoto. At Loviisa 10 mSv doses are restricted mainly inside the PAZ. Calculations show that outside the 20 km radius the 6 mSv is unlikely to exceed. At Olkiluoto the dose for children is higher, being 15-20 mSv inside the PAZ and nearby areas outside of it. 10 mSv doses should stay within the EPZ.

Doses for unprotected children in very large cases are shown in figure 8.25 for Loviisa and in figure 8.25 for Olkiluoto. At Loviisa the maximum doses are between 100-120 mSv near the power plant. Between 5-20 km zones the doses are 40-100 mSv. The area of 10 mSv dose spreads to eastern Porvoon, southern Kouvola and southern Hamina outside the EPZ. 20 mSv is exceeded in the Loviisa-Pyhtää-Kotka area. At Olkiluoto the doses are a bigger. Near the NPP the maximum values are 150-180 mSv. 50-150 mSv doses are exceeded in almost every scenario inside the 20 km zone. The 10 mSv dose are reaches over Pori in the north, western Sastamala in the east and southern Laitila in the south outside the EPZ and the 20 mSv stays within Pori-Ulvila-Rauma region.

Thyroid dose

Thyroid dose during the first week for unprotected adults in large cases are illustrated in figure 8.26 at Loviisa site and in figure 8.27 at Olkiluoto site. For Loviisa the maximum doses are in the range of 50-60 mSv and exceed the PAZ for few kilometers. Outside the EPZ the thyroid dose is likely to stay under 30 mSv. The doses over 20 mSv do not seem to reach Kotka at north-west direction. At Olkiluoto the maximum thyroid doses are 80-100 mSv spred out rather similarly inside and outside the 5 km zone as at the Loviisa site. Outside the 20 km zone the mainly stay below 40 mSv and the 20 mSv are reaches to southern parts of Pori in the north and western parts of Rauma in the south.

For very large release case the adult thyroid doses during the first week are shown in figure 8.28 for Loviisa and in figure 8.29 for Olkiluoto. Very large case shows significant doses during the first week. At Loviisa the maximum thyroid doses are 500-600 mSv and inside the 20 km zone the dose can reach 400 mSv. 100 mSv can be exceeded east from Loviisa Kotka and Hamina. At Olkiluoto maximum dose can elevate up to 1 Sv inside the PAZ. Nearly for every scenario the 200 mSv is exceeded outside the EPZ. 100 mSv thyroid doses are possible from the north-western parts of Pori to south-eastern parts of Rauma.

Thyroid doses during the first week calculated for unprotected children are shown for Loviisa large case in figure 8.30 and for Olkiluoto large case in figure 8.31. At Loviisa the maximum thyroid dose for children 160 mSv is about three times the maximum values for adults. This dose is very local and effectively the maximum value can be considered to be circa 150 mSv. 10 mSv thyroid dose is exceeded circa 85 km from the NPP under some weather conditions. The possible 10 mSv dose area consists Kotka, Hamina and southern Kouvola. Eastern Porvoo can be affected with this thyroid dosage as well. At Olkiluoto the maximum doses are in the range of 200-260 mSv at the coastline of south-western Eurajoki. Within the 20 km zone 100 mSv is exceeded in almost every scenario. The possible are of having 10 mSv thyroid doses extends to Merikarvia in the north, to western Sastamala in the east, and to Laitila in the south. 100 km zone is not exceeded in either of the sites.

Very large cases for unprotected children's first week's thyroid dose are illustrated in figure 8.32 for Loviisa and for Olkiluoto a corresponding illustration is found in the figure 8.33. At Loviisa case the maximum doses reach circa 1.5 Sv inside and near the PAZ. Inside the EPZ is expected to have 600-800 mSv doses. The possible 10 mSv area expands over the 100 km zone. Helsinki and Hämeenlinna in the west, Mikkeli in the north, and Savonlinna in the north-east are the furthest large cities possibly affected. At Olkiluoto doses at the Eurajoki south-western coastline can reach even 2.5 Sv. Inside the EPZ 1.2 Sv doses can be expected nearly in all weather cases. The 10 mSv area can reach areas far outside the 100 km zone, even Helsinki in the south-east, Jyväskylä in the east, Kokkola in the north (out of the range of figure 8.33), and Turku in the south.

8.4 General observations

It can be observed that the in every case and every studied quantity the results follow the directions indicated by the wind roses (see figures 5.2 and 5.3).

In general, the results show consistency to the magnitude of the release. Therefore, the results can be considered feasible at this point of view. The results show continuity in the data, so the calculation grid works as desired.

8.5 Comparison to the VAL-guide's dose critera and operational intervention levels

This section compares the results of this study to the operational intervention levels and other threshold values behind them from the VAL-guides considering protective actions. This comparison is done simply by checking if the threshold value exceeds outside the 20 km zone, which is approximated to be the EPZ. The only exceptions are the dose rate of 100 μSv/h and air concentration of strong gamma emitters being over 10 kBq/m^3, which were observed as the function of the duration when these values were exceeded. These are compared to those quantities which are an alternative measure of protective actions or the motivation of some intervention level. Since 48 hour time integration interval showed no significant results, the one week time interval is used as an approximation for in which areas it is possible that the dose criteria is exceeded within some 48 hour time frame.

Strong gamma emitter deposition after 48 hours, dose and thyroid dose for adults and children during the first week are compared to dose criteria, and for deposition to operational intervention level, in table 8.1. It is observed that the affected areas are consistent case-wise for both Loviisa and Olkiluoto sites.

For the basic case none of the criteria or intervention level is exceeded. In large case the gamma emitter deposition OIL exceeds the EPZ in some weather scenarios as well as the thyroid dose criterion for children. External dose criterion for children exceeds within the limits of the EPZ. For adults, neither thyroid or external dose criteria is exceeded in the large case.

For very large case all the above criteria and OILs are exceeding the EPZ. Gamma emitter deposition OIL and thryoid dose criterion for children spreads over the 100 km radius in some weather scenarios.

Considering duration when OILs of strong gamma emitter air concentration (10 kBq/m^3) and dose rate (100 μSv/h) are exceeded, were significant only in very large case. It is observed that the dose rate duration is much longer with maximum of 48 hours whereas the gamma emitter air concentration stays 5-6 hours or under. For Loviisa the 48 hour area is smaller than for Olkiluoto. All the duration maps are consistent in case of direction compared to deposition and doses.

8.5.1 Contamination levels

Considering contamination levels via fallout, results show that it is probable that extremely heavy contamination occurs both in large and very large cases for both sites. For large case this area remains under 100 km zone but for very large case it is exceeded.

When observing the dose rate of 100 μSv/h the extremely contaminated area stays within EPZ for the longest periods of time in the Loviisa very large case and exceeds with few kilometers in some weather scenarios at Olkiluoto. Outside the EPZ extremely contaminated area is that for less than 6 hours, if dose rate is the observable.

TABLE 8.1: Comparison of the results and VAL-guide dose criteria and operational intervention levels.

Dose criterion / OIL distance:	*5-20 km: X*	BASIC		LARGE		VERY LARGE	
20-100 km: XX	*> 100 km : XXX*	LO	OL	LO	OL	LO	OL
Strong γ emitter deposition (after 48 hours) ≥10 MBq/m^2 *sheltering indoors – intermediate phase*		–*	–*	XX	XX	XXX	XXX
Dose ≥ 10 mSv, adults (week) *Sheltering indoors – early and intermediate phases*		–*	–*	–*	–*	XX	XX
Dose ≥ 10 mSv, children (week) *Sheltering indoors – early and intermediate phases*		–*	–*	X	X	XX	XX
Dose ≥ 20 mSv, adults (week) *evacuation – early and intermediate phases*		–*	–*	–*	–*	XX	XX
Dose ≥ 20 mSv, children (week) *Evacuation – early and intermediate phases*		–*	–*	–*	–*	XX	XX
Thyroid dose (week) ≥ 100 mSv, adults *iodine prophylaxis – early phase*		–*	–*	–*	–*	XX	XX
Thyroid dose (week) ≥ 10 mSv, 1 y/o children *iodine prophylaxis – early phase*		–*	–*	XX	XX	XXX	XXX

*Dose criterion/OIL not exceeded in the scenario.

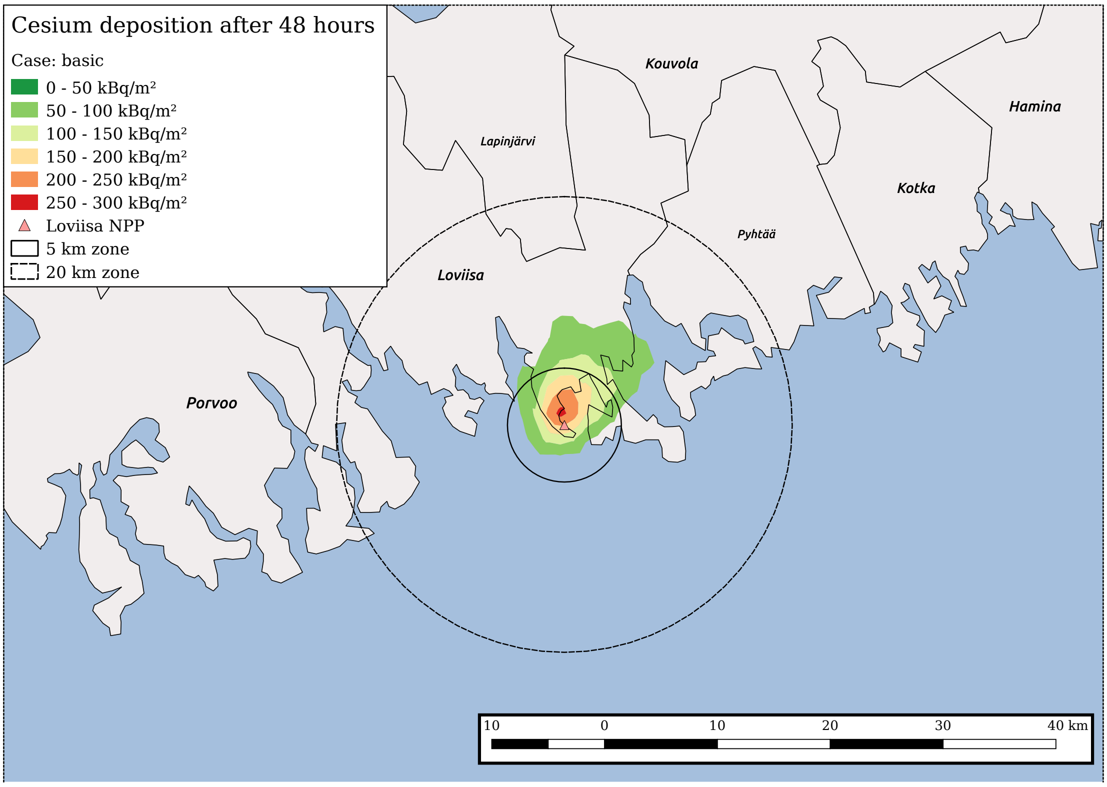

FIGURE 8.4: Combined ^{137}Cs and ^{134}Cs deposition after 48 hours in Loviisa basic case.

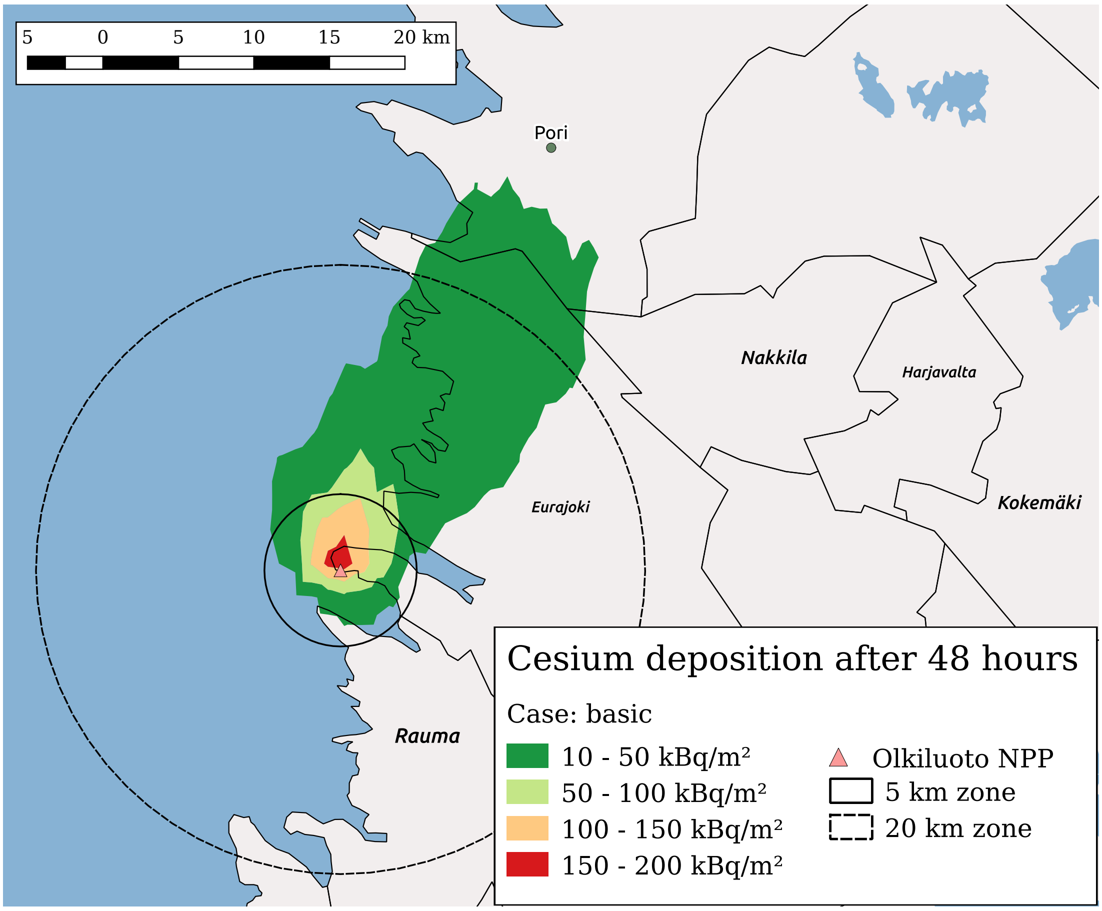

FIGURE 8.5: Combined ^{137}Cs and ^{134}Cs deposition after 48 hours in Olkiluoto basic case.

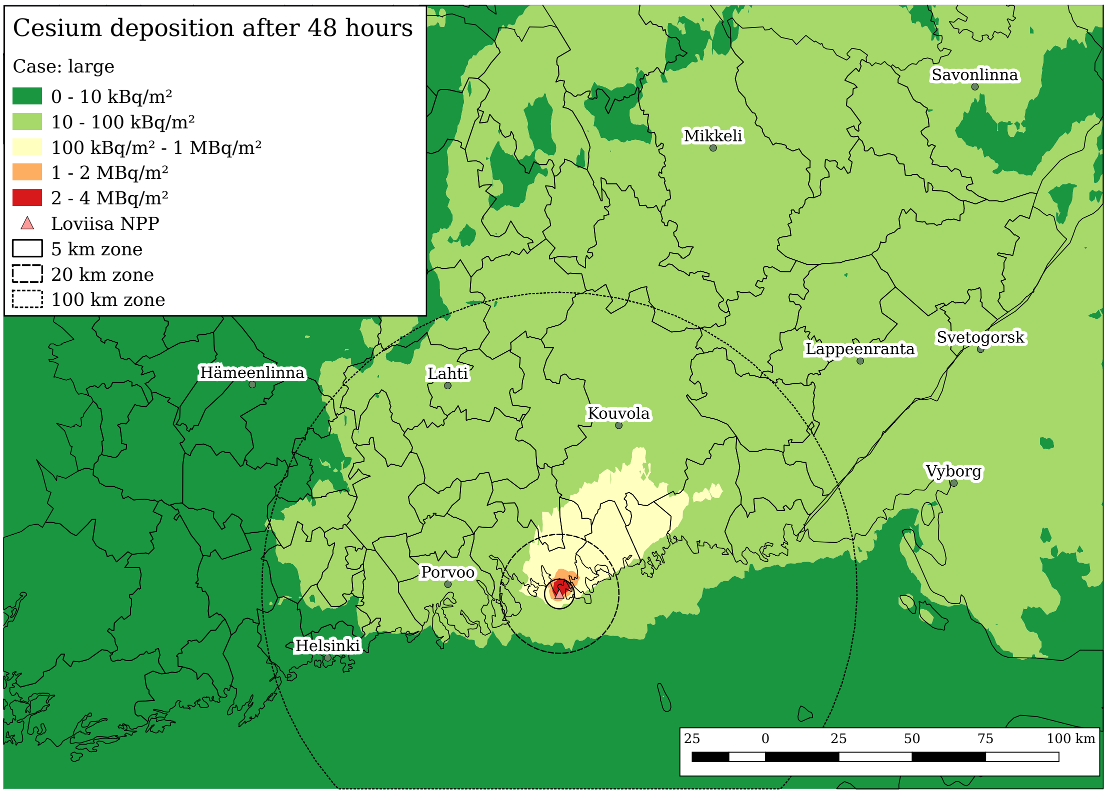

FIGURE 8.6: Combined ^{137}Cs and ^{134}Cs deposition after 48 hours in Loviisa large case.

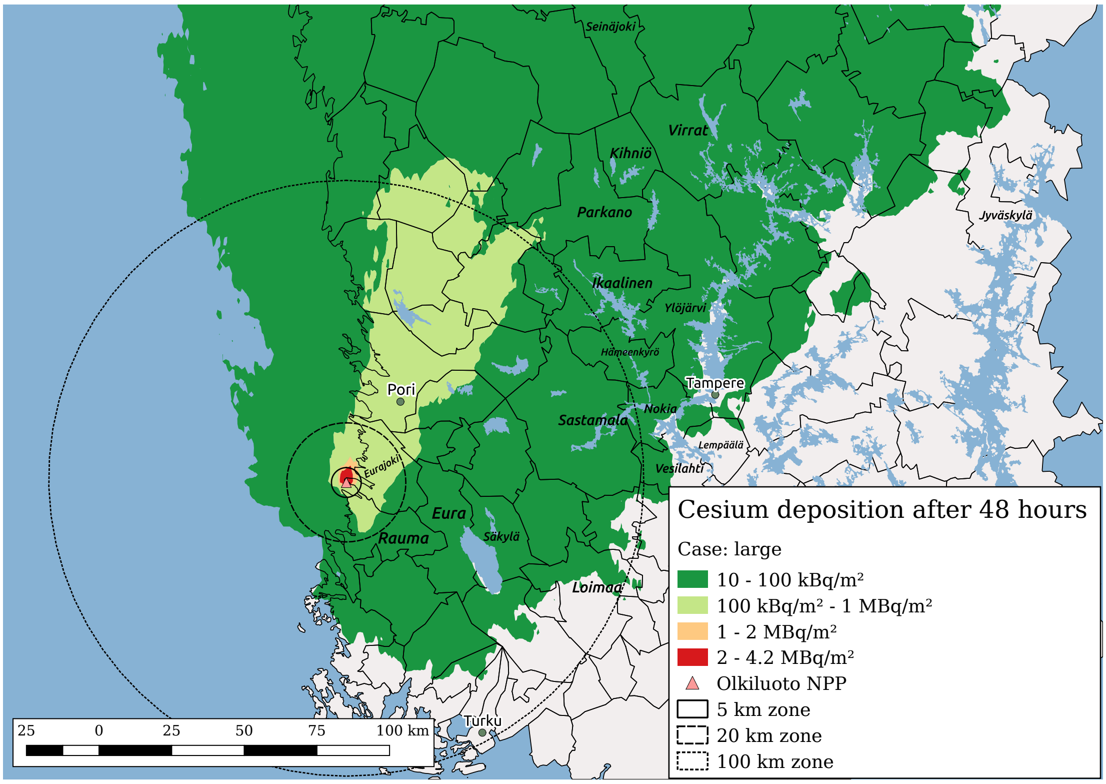

FIGURE 8.7: Combined ^{137}Cs and ^{134}Cs deposition after 48 hours in Olkiluoto large case.

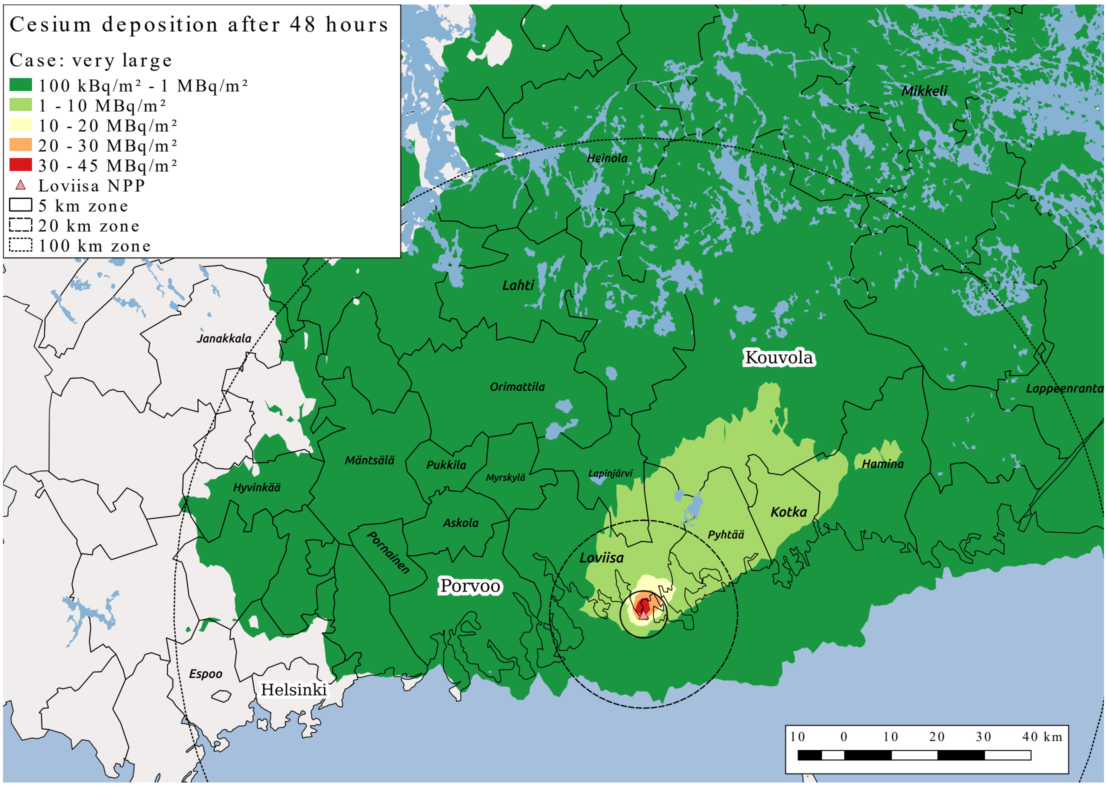

FIGURE 8.8: Combined ^{137}Cs and ^{134}Cs deposition after 48 hours in Loviisa very large case.

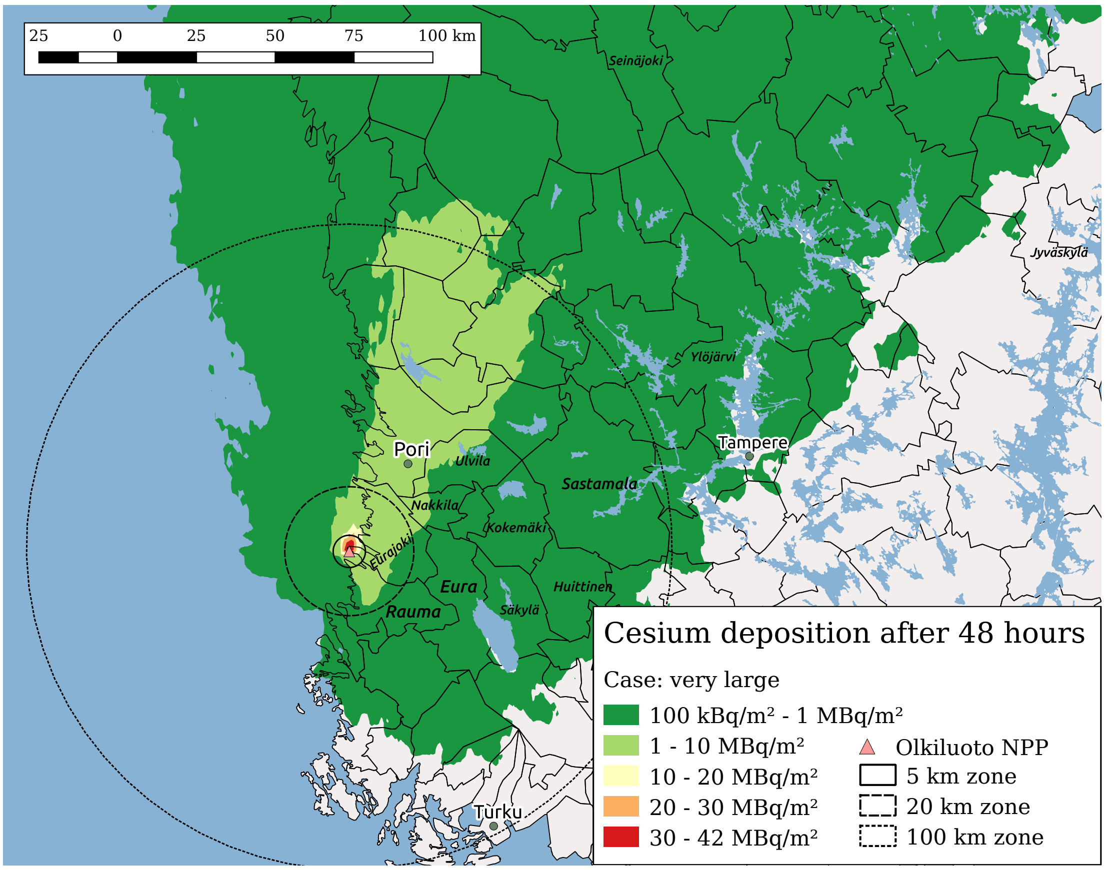

FIGURE 8.9: Combined ^{137}Cs and ^{134}Cs deposition after 48 hours in Olkiluoto very large case.

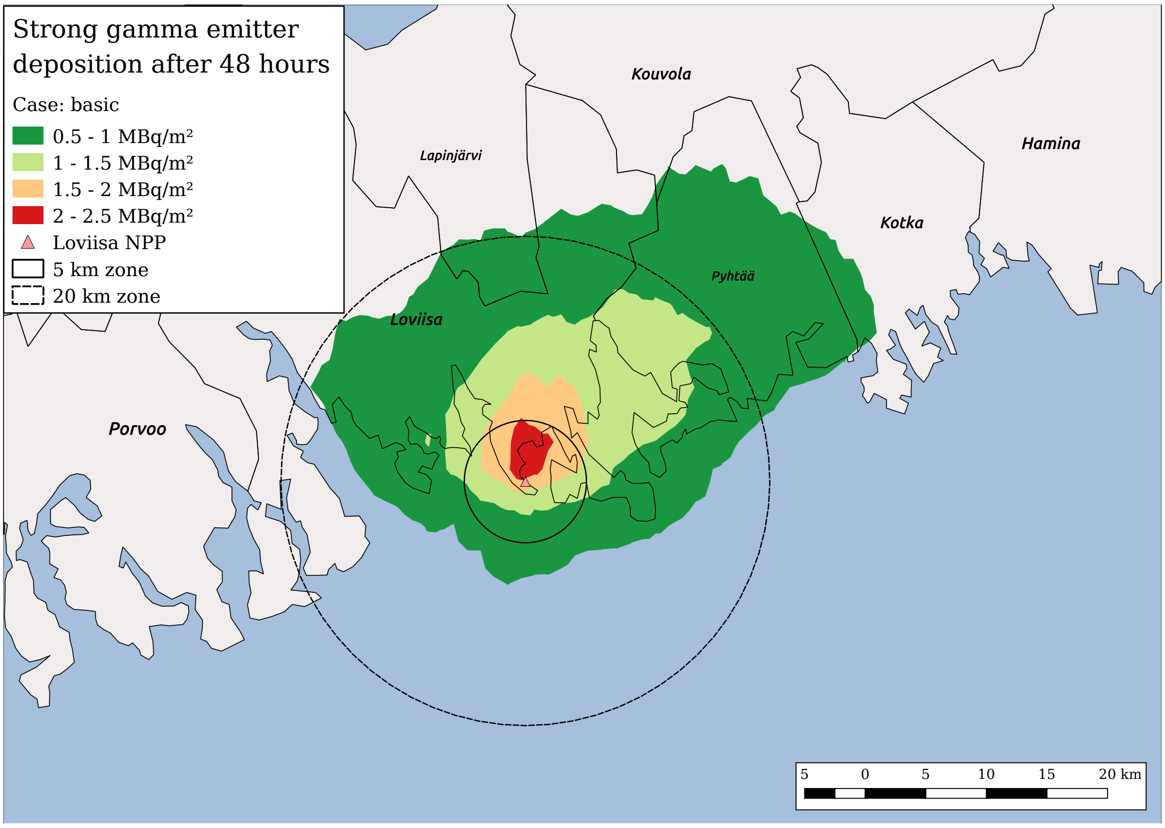

FIGURE 8.10: Strong gamma emitter deposition after 48 hours in Loviisa basic case.

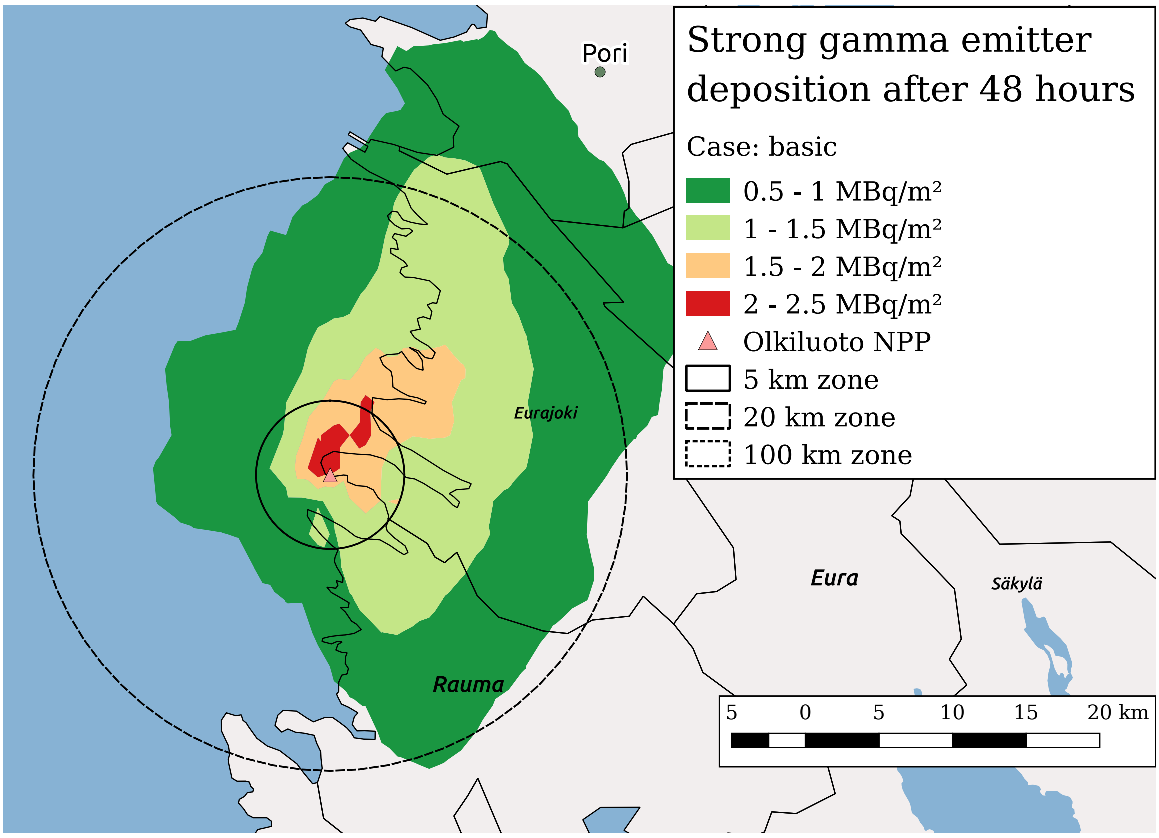

FIGURE 8.11: Strong gamma emitter deposition after 48 hours in Olkiluoto basic case.

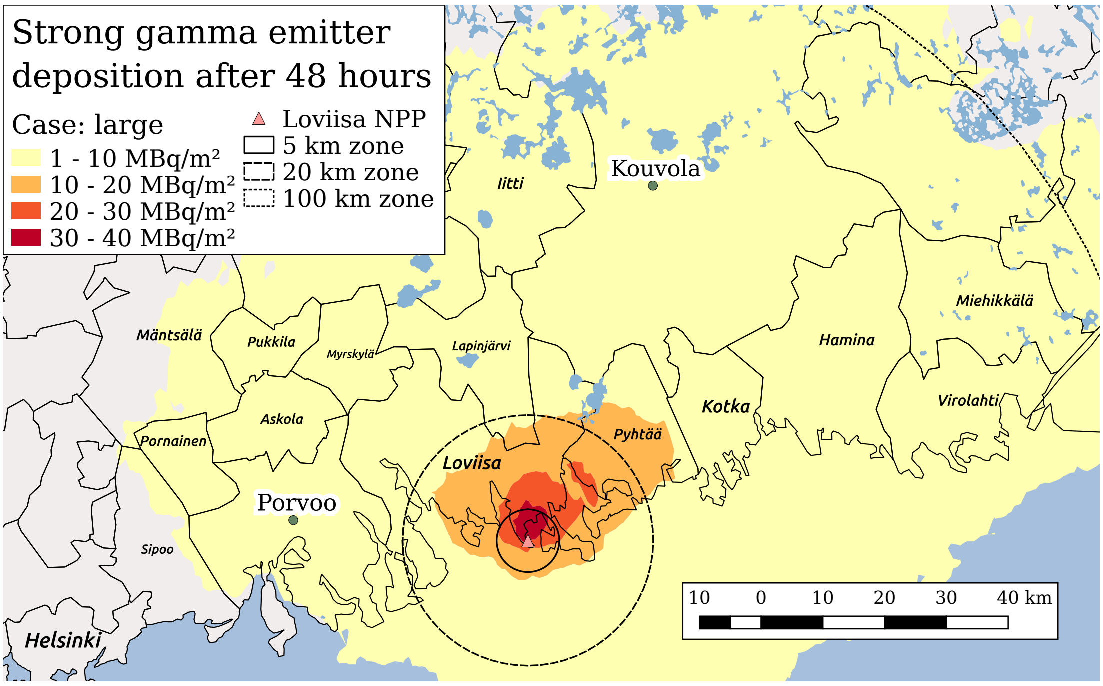

FIGURE 8.12: Strong gamma emitter deposition after 48 hours in Loviisa large case.

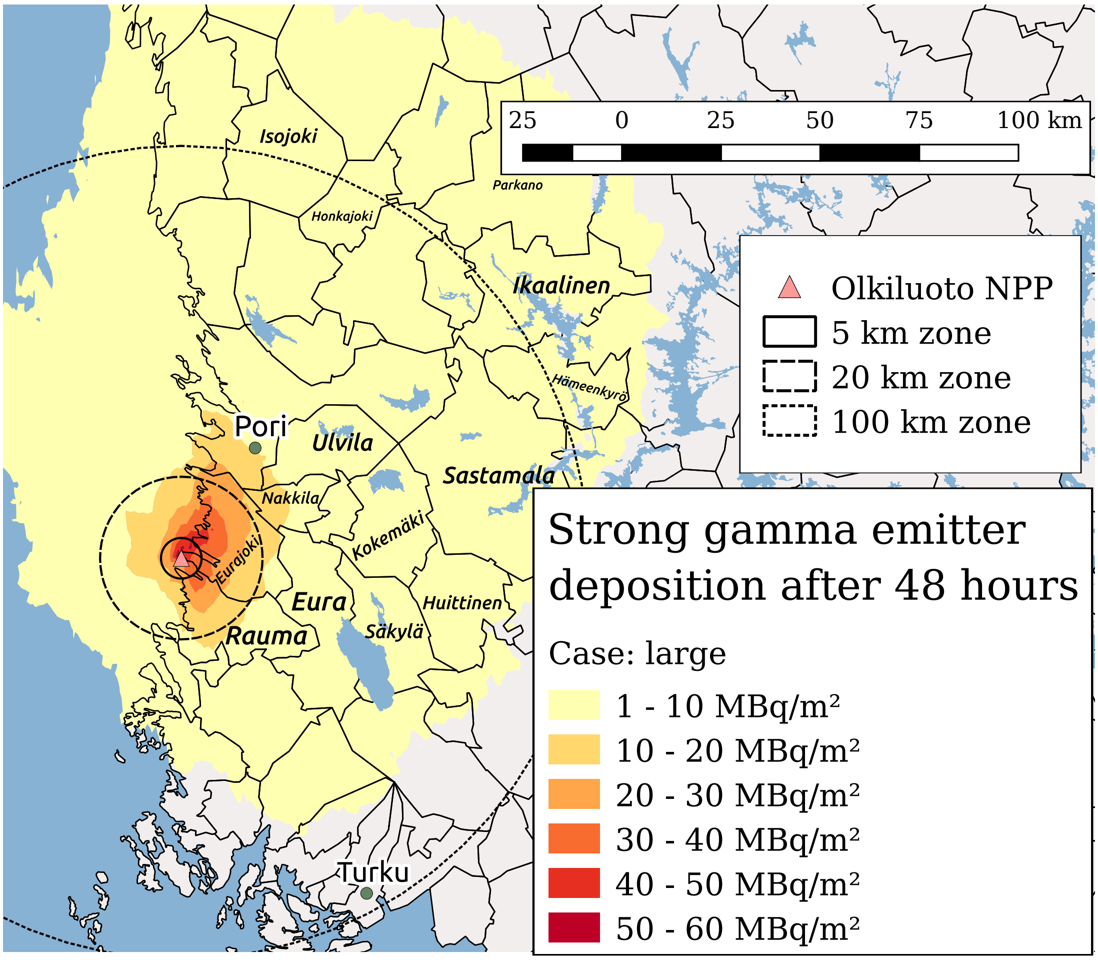

FIGURE 8.13: Strong gamma emitter deposition after 48 hours in Olkiluoto large case.

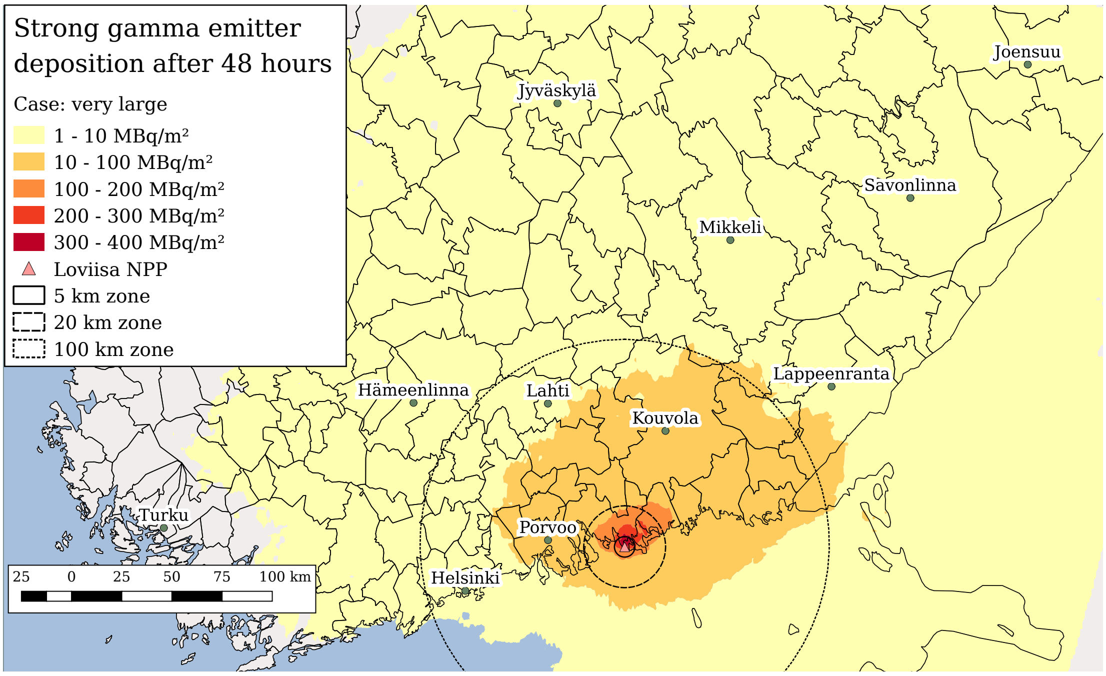

FIGURE 8.14: Strong gamma emitter deposition after 48 hours in Loviisa very large case.

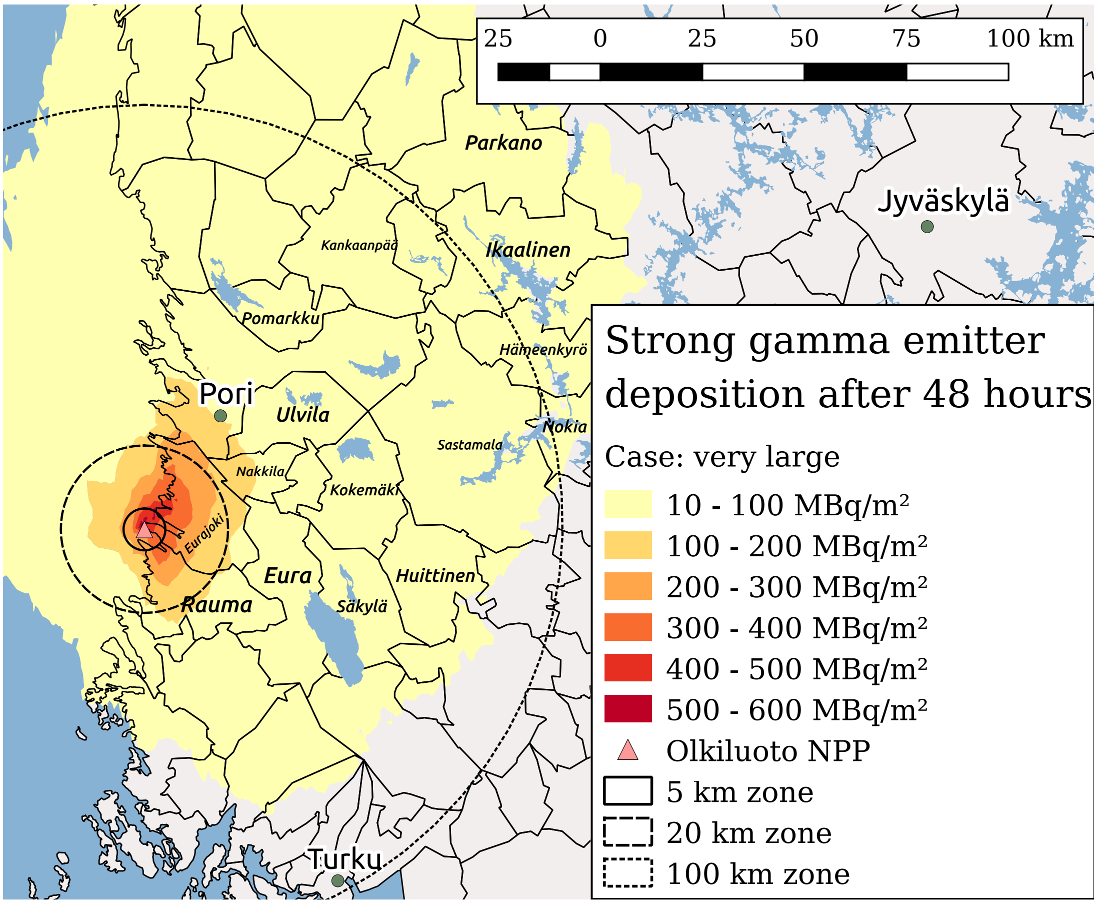

FIGURE 8.15: Strong gamma emitter deposition after 48 hours in Olkiluoto very large case.

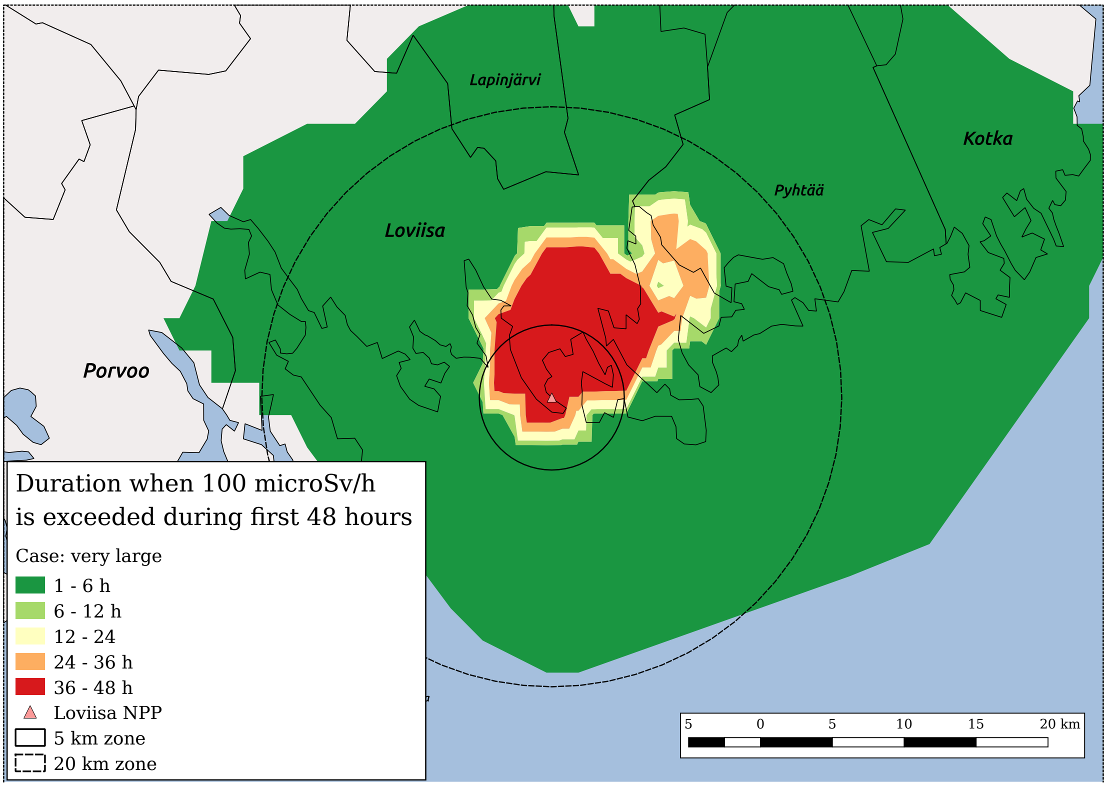

FIGURE 8.16: Time map of Loviisa very large case for duration when dose rate 100 μSv/h is exceeded.

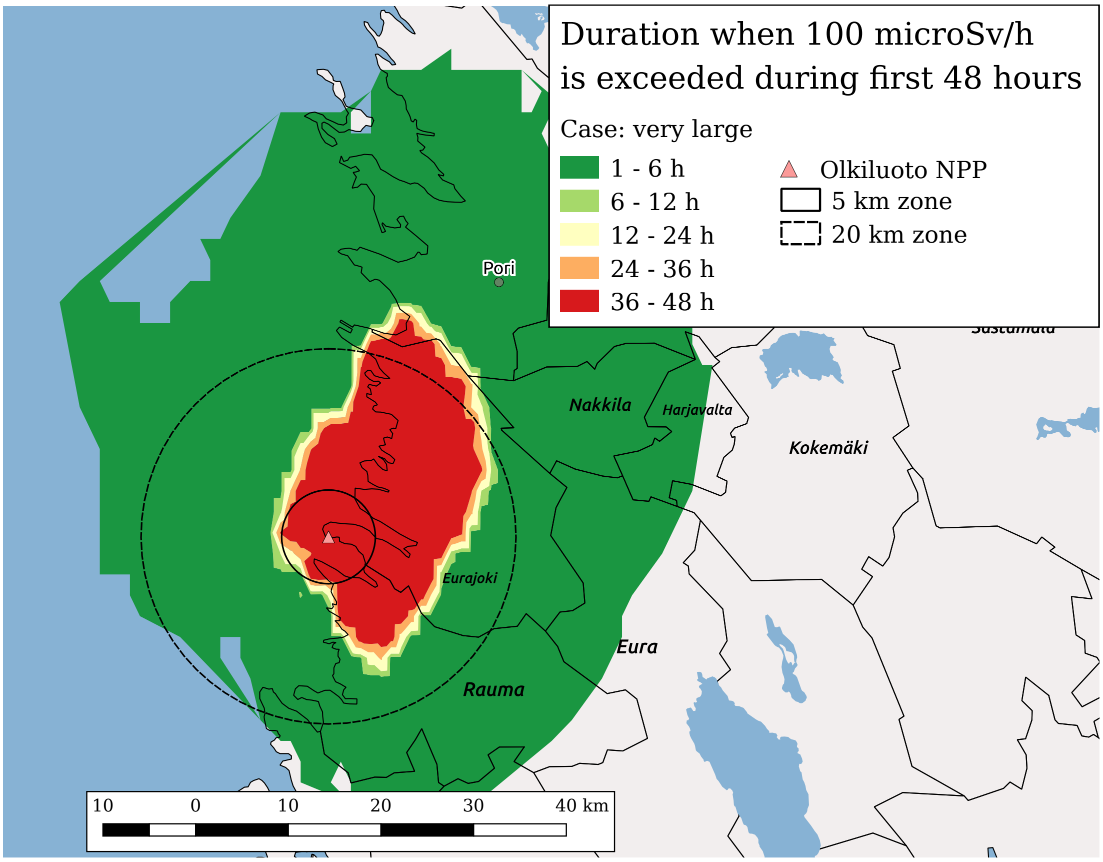

FIGURE 8.17: Time map of Olkiluoto very large case for duration when dose rate 100 μSv/h is exceeded.

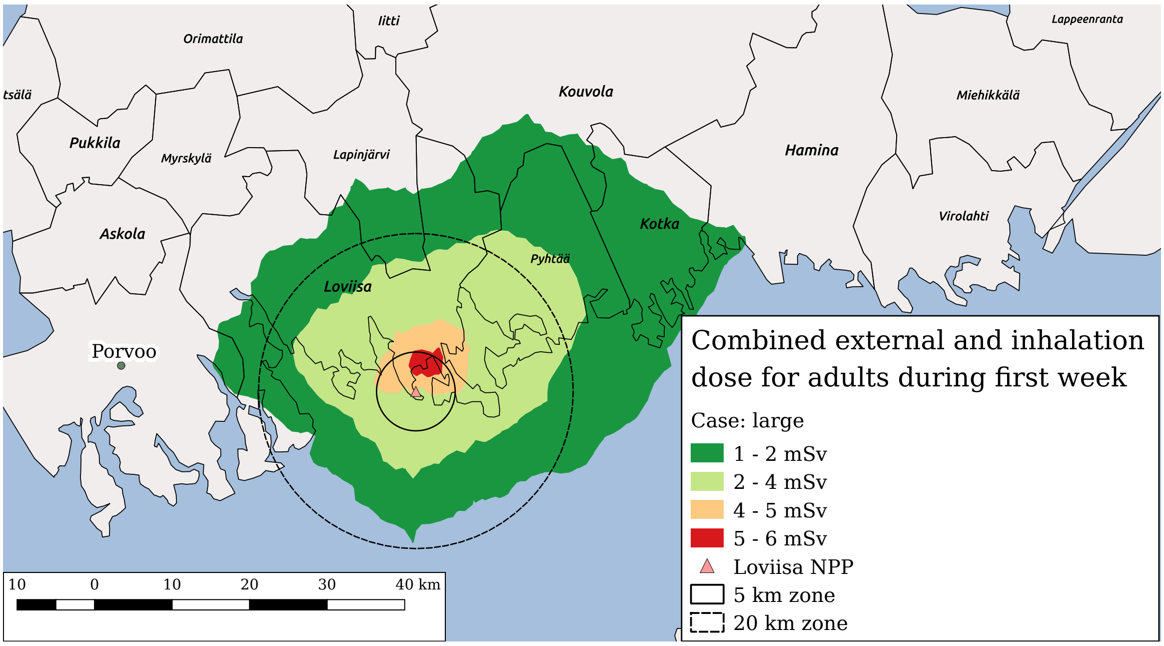

FIGURE 8.18: Dose via inhalation and external exposure for unprotected adults during first week in Loviisa large case.

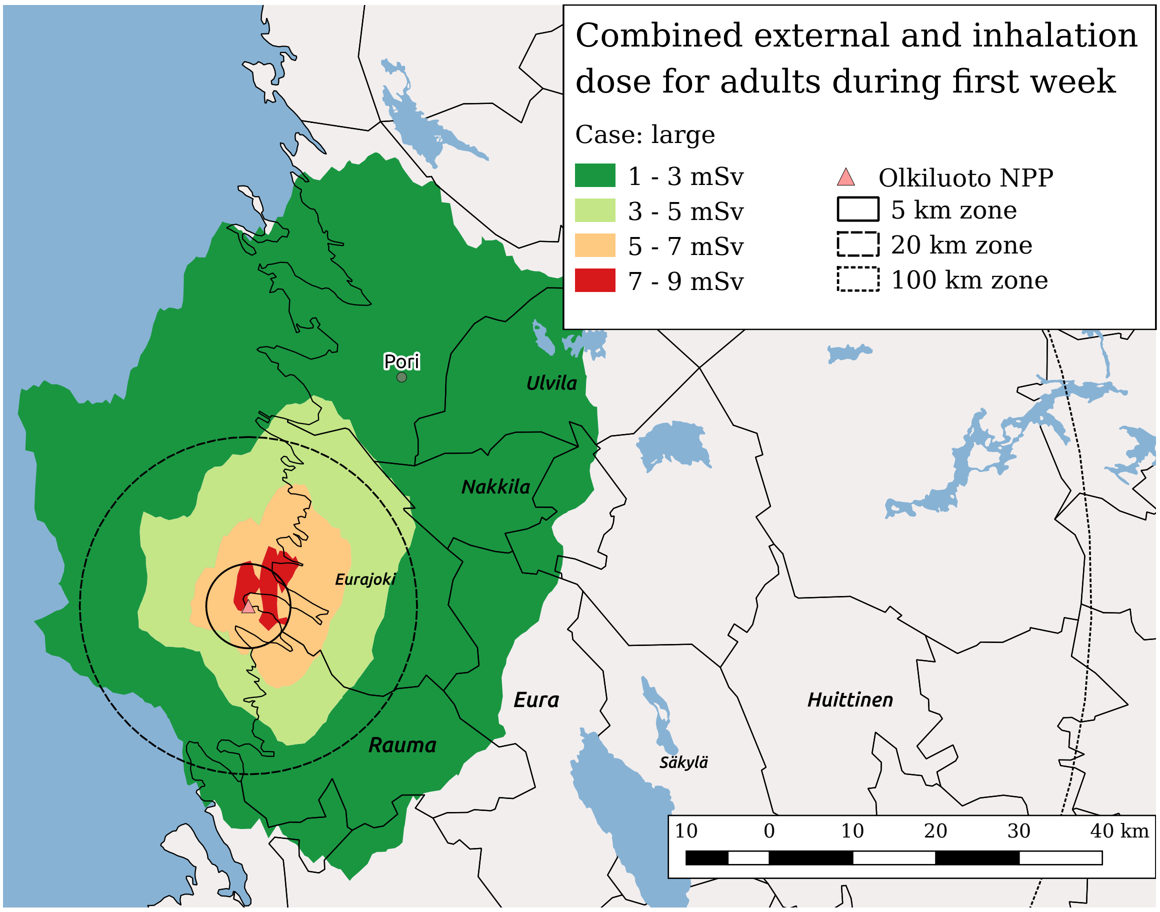

FIGURE 8.19: Dose via inhalation and external exposure for unprotected adults during first week in Olkiluoto large case.

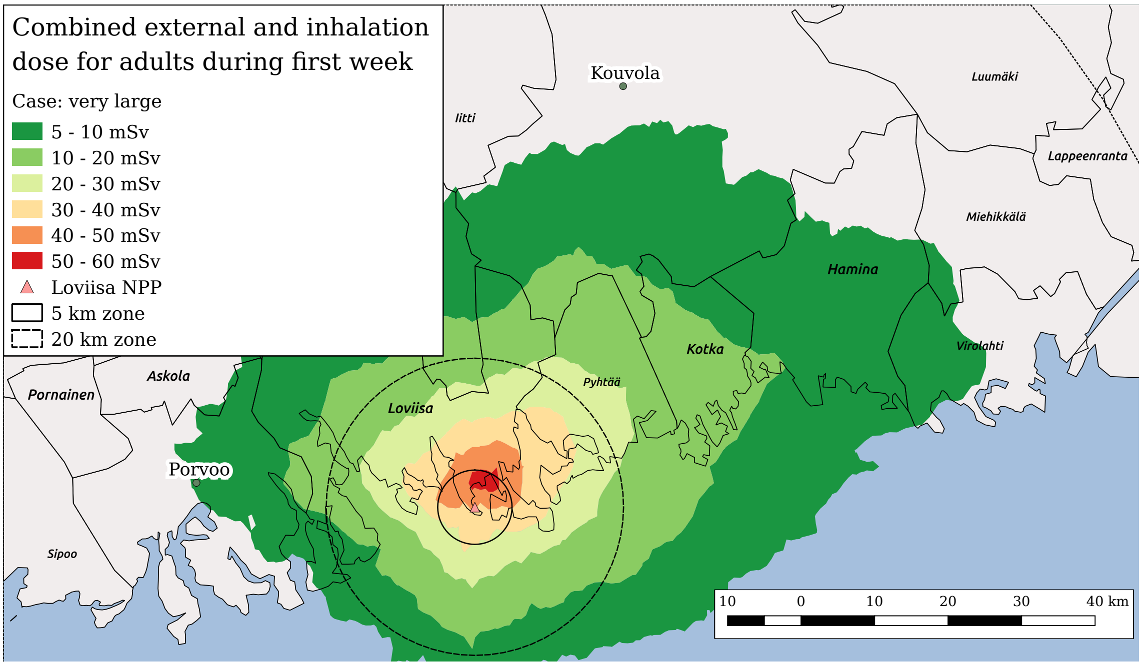

FIGURE 8.20: Dose via inhalation and external exposure for unprotected adults during first week in Loviisa very large case.

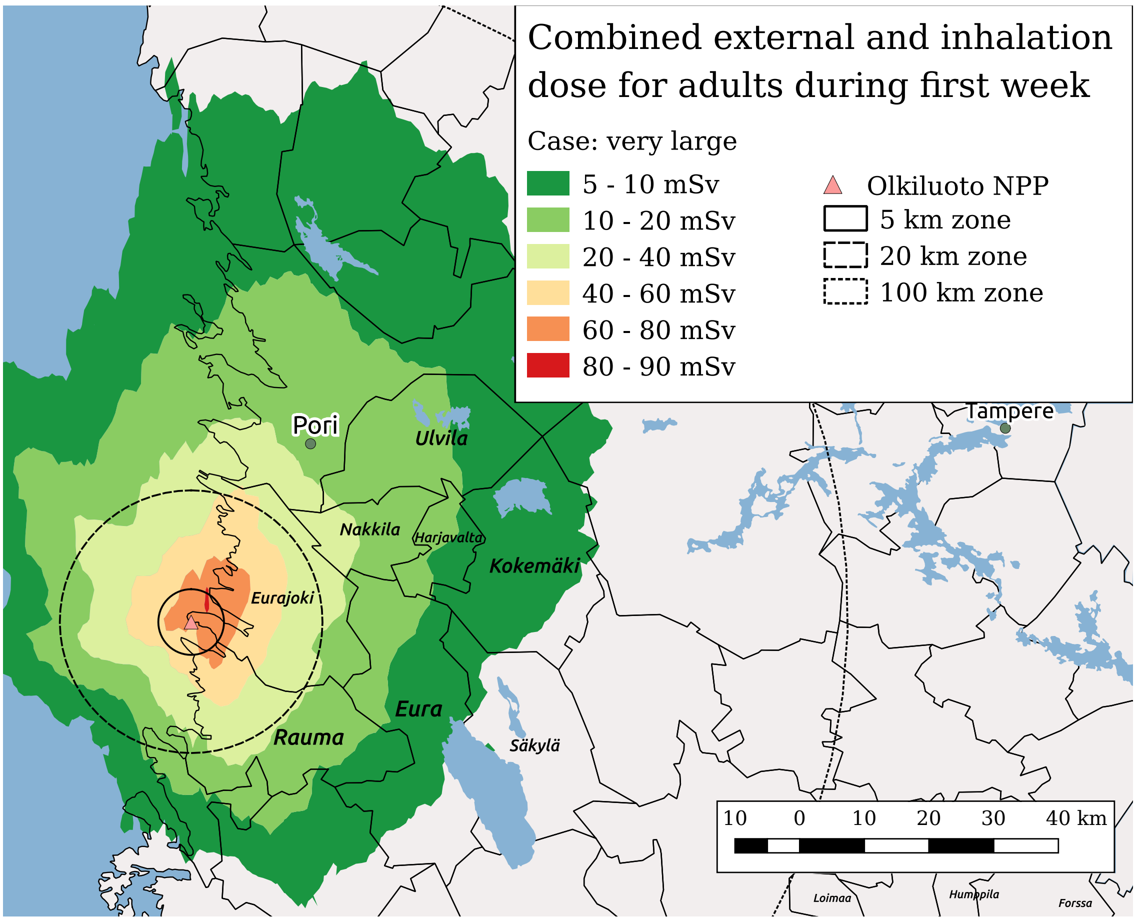

FIGURE 8.21: Dose via inhalation and external exposure for unprotected adults during first week in Olkiluoto very large case.

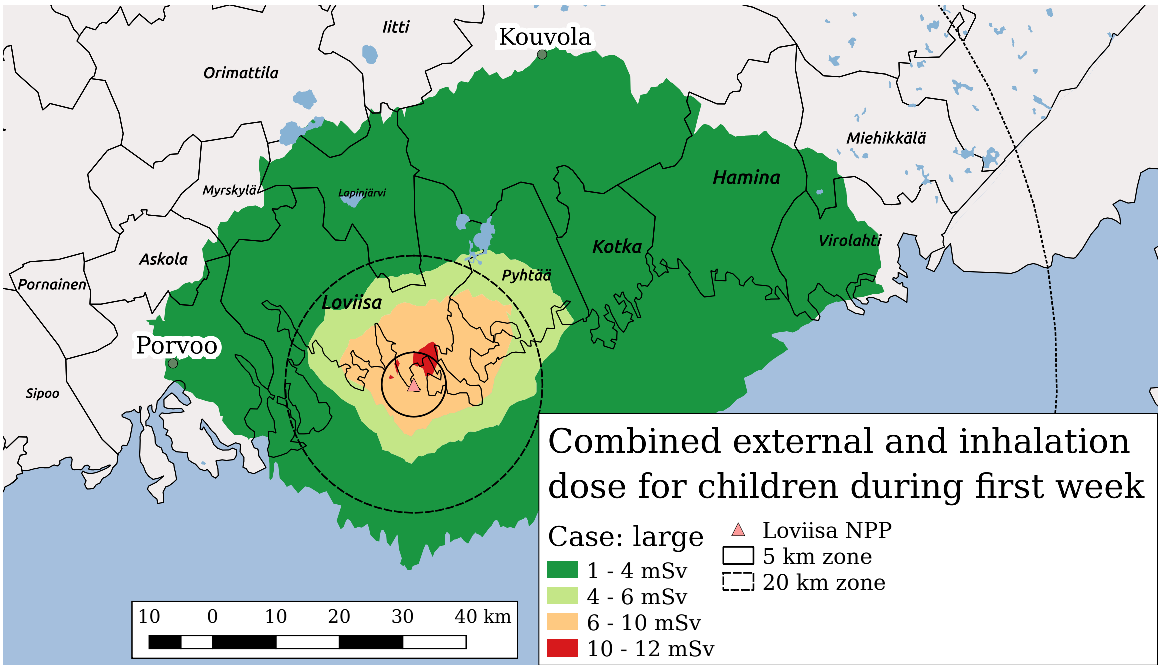

FIGURE 8.22: Dose via inhalation and external exposure for 1 year old unprotected children during first week in Loviisa large case.

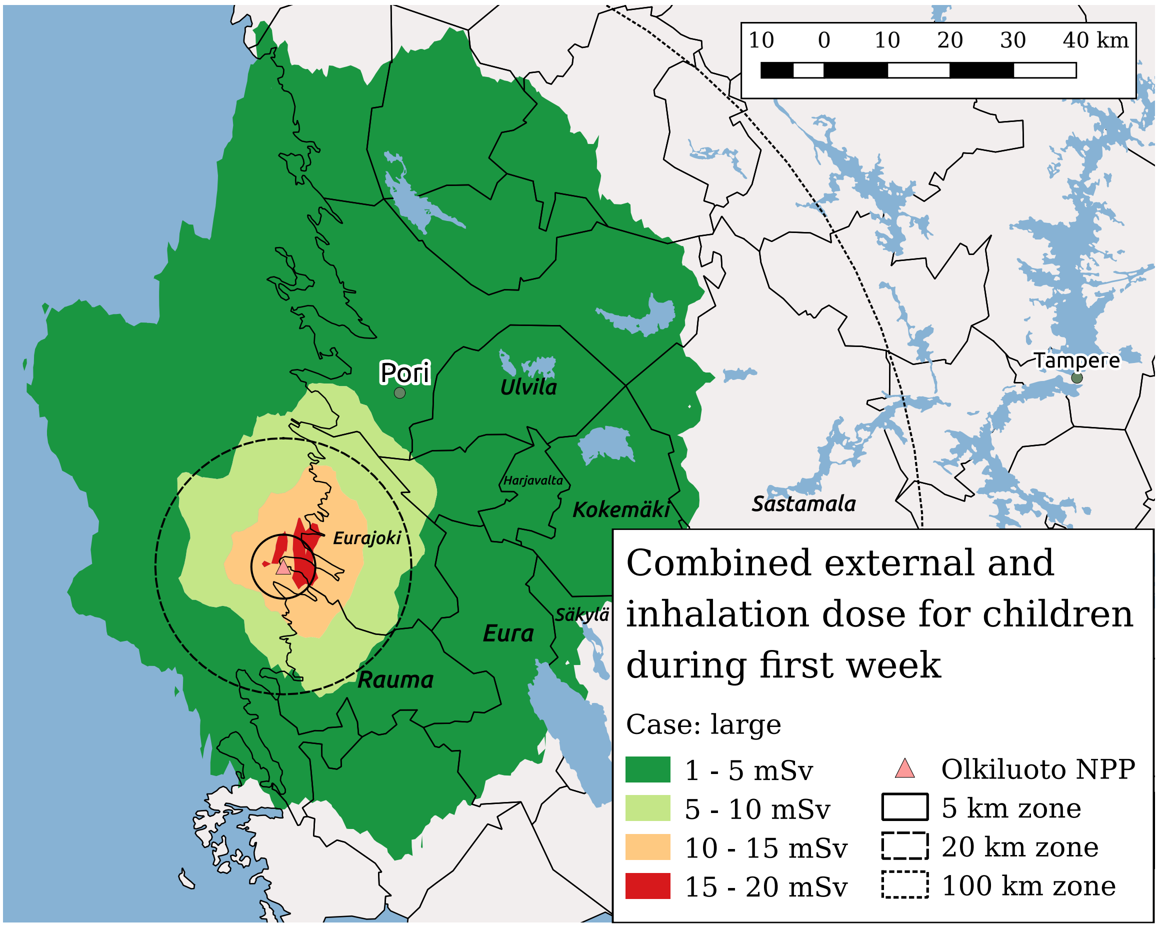

FIGURE 8.23: Dose via inhalation and external exposure for 1 year old unprotected children during first week in Olkiluoto large case.

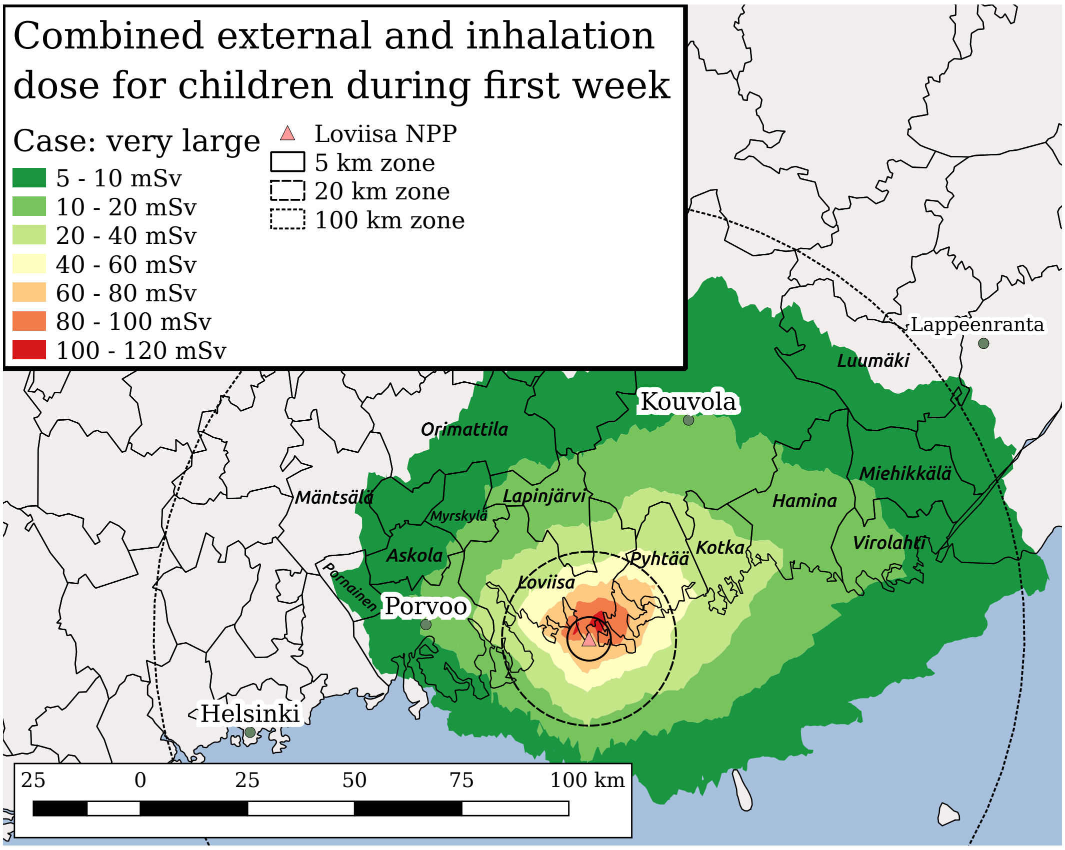

FIGURE 8.24: Dose via inhalation and external exposure for 1 year old unprotected children during first week in Loviisa very large case.

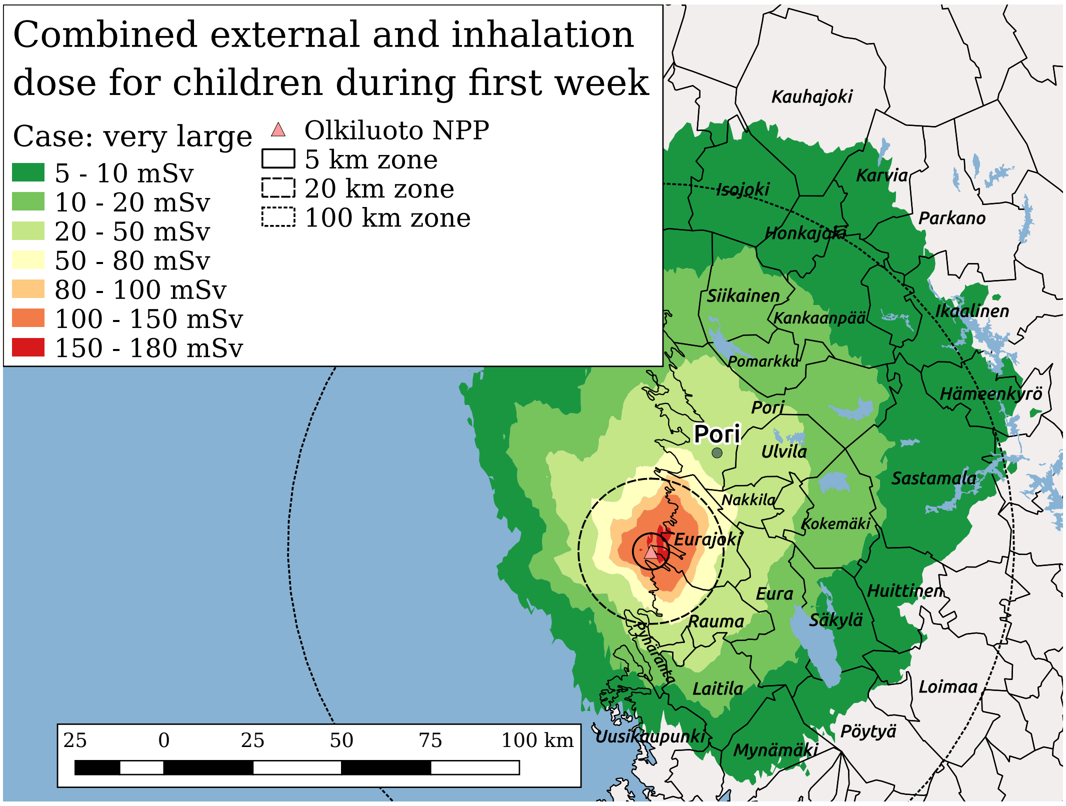

FIGURE 8.25: Dose via inhalation and external exposure for 1 year old unprotected children during first week in Olkiluoto very large case.

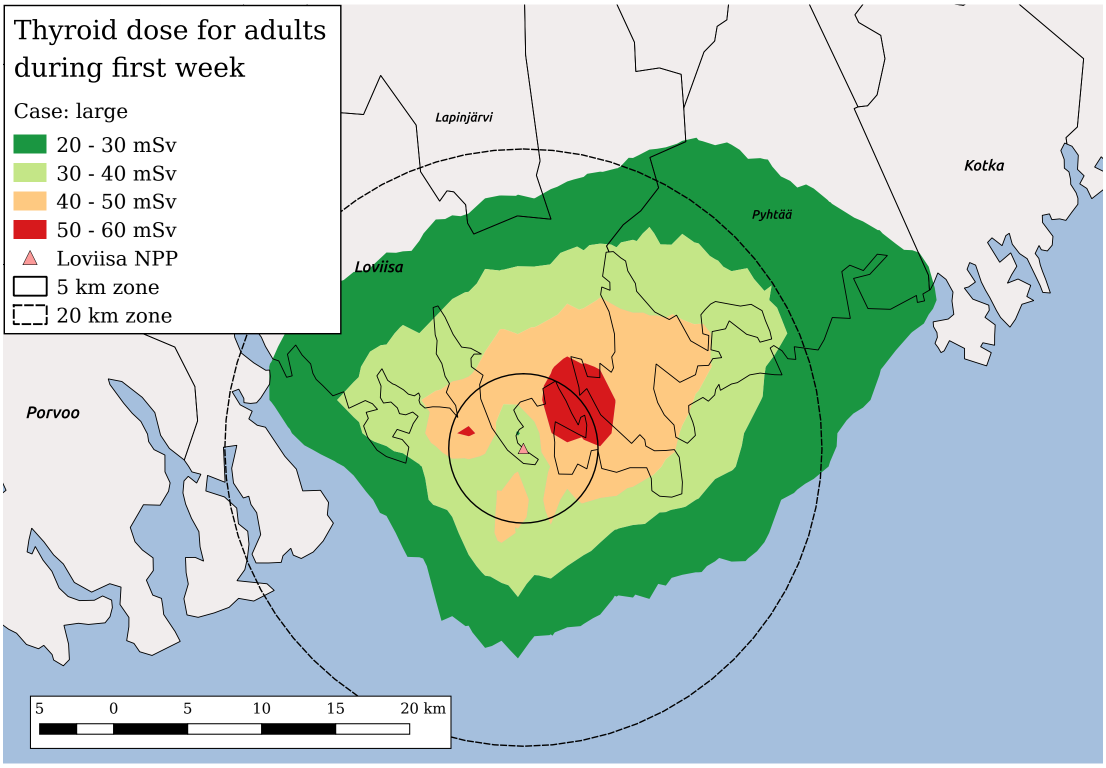

FIGURE 8.26: Thyroid dose for unprotected adults during first week in Loviisa large case.

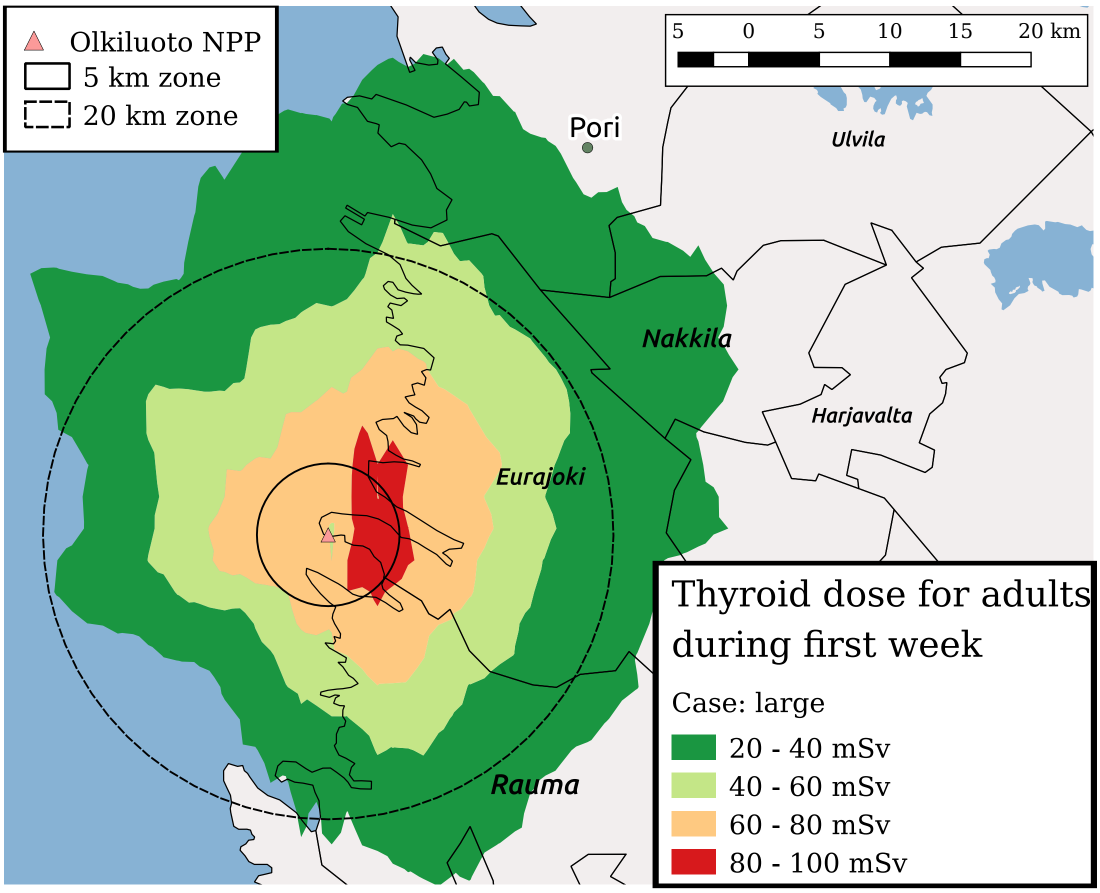

FIGURE 8.27: Thyroid dose for unprotected adults during first week in Olkiluoto large case.

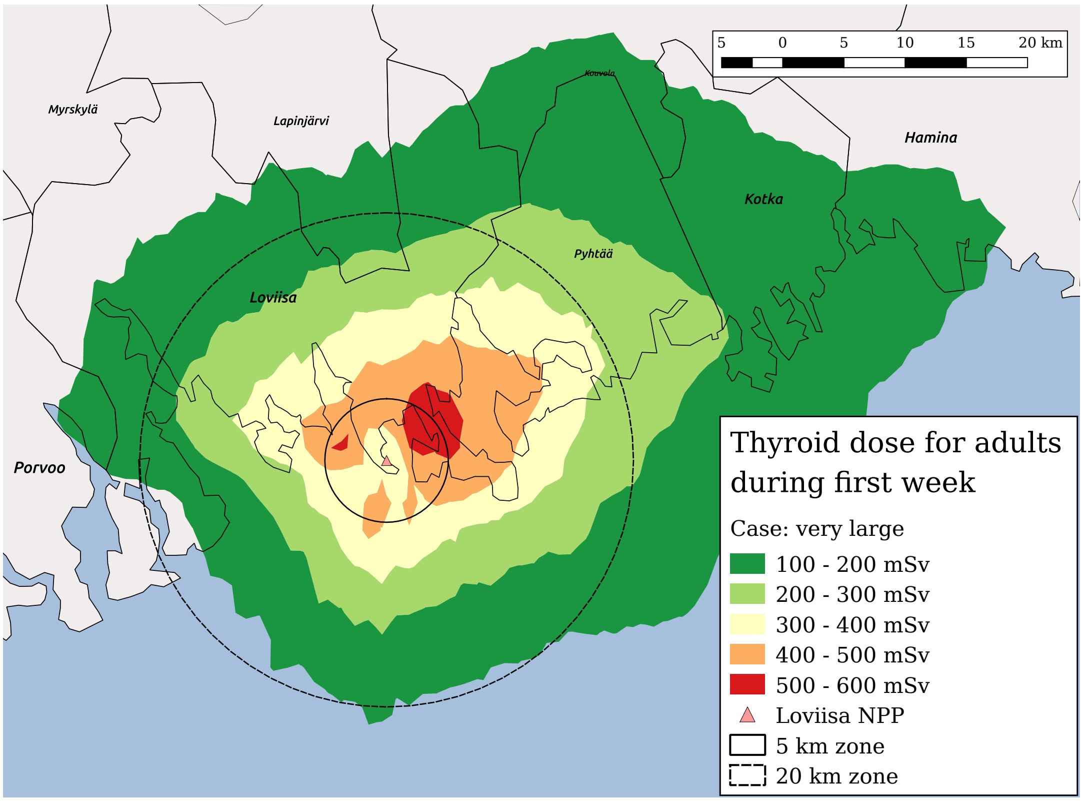

FIGURE 8.28: Thyroid dose for unprotected adults during first week in Loviisa very large case.

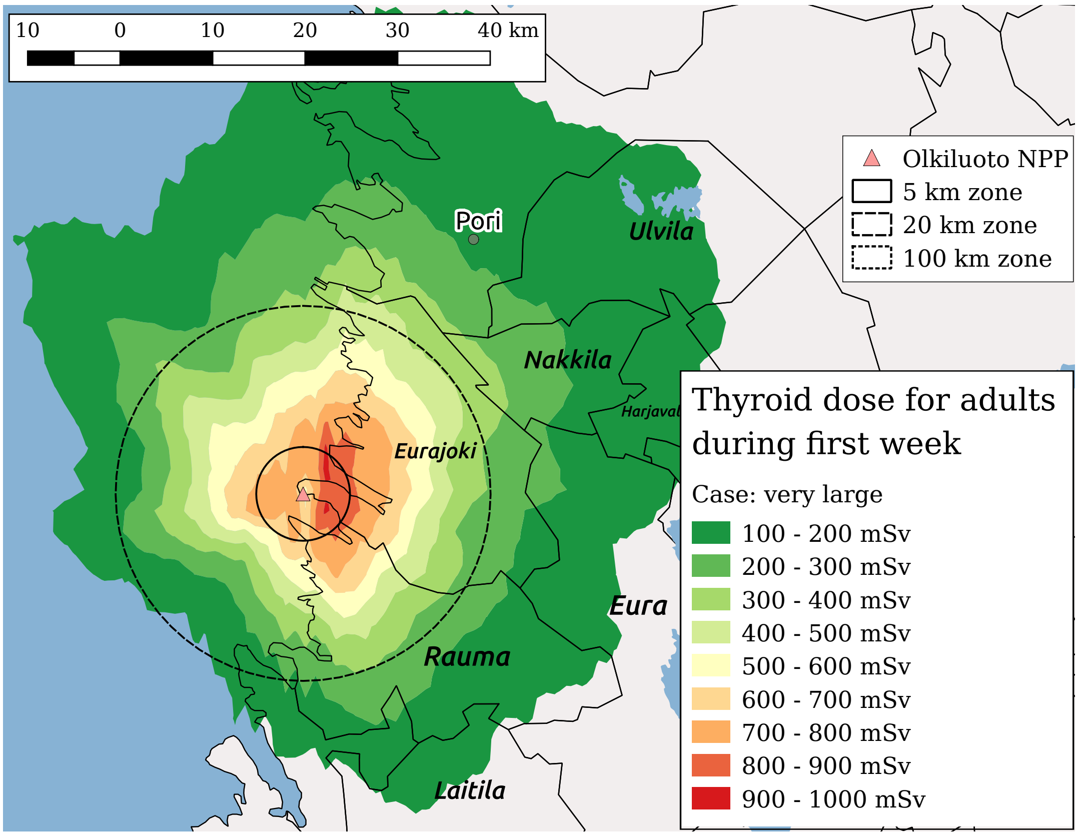

FIGURE 8.29: Thyroid dose for unprotected adults during first week in Olkiluoto very large case.

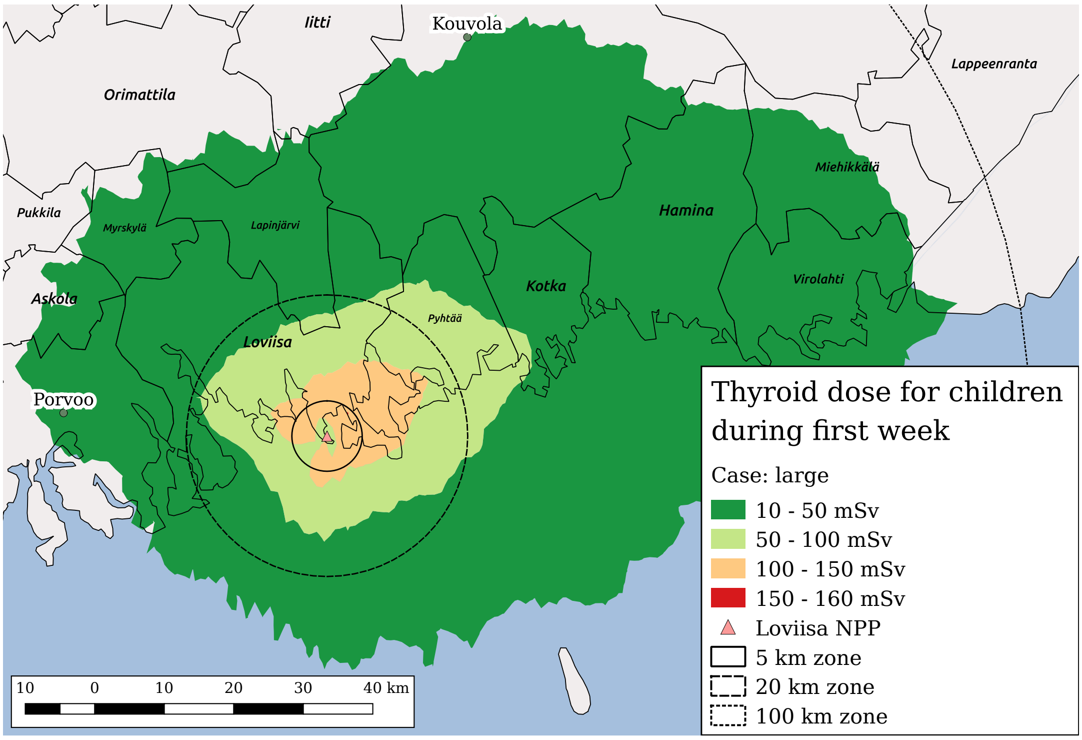

FIGURE 8.30: Thyroid dose for 1 year old unprotected children during first week in Loviisa large case.

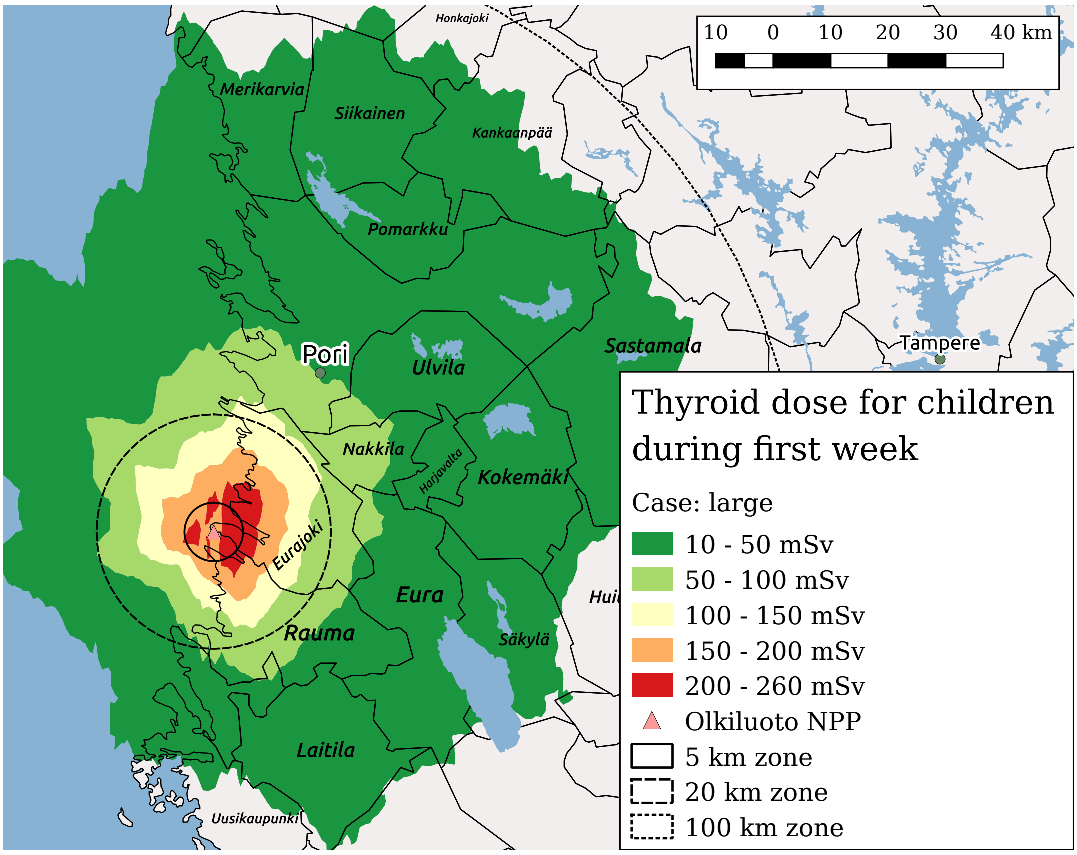

FIGURE 8.31: Thyroid dose for 1 year old unprotected children during first week in Olkiluoto large case.

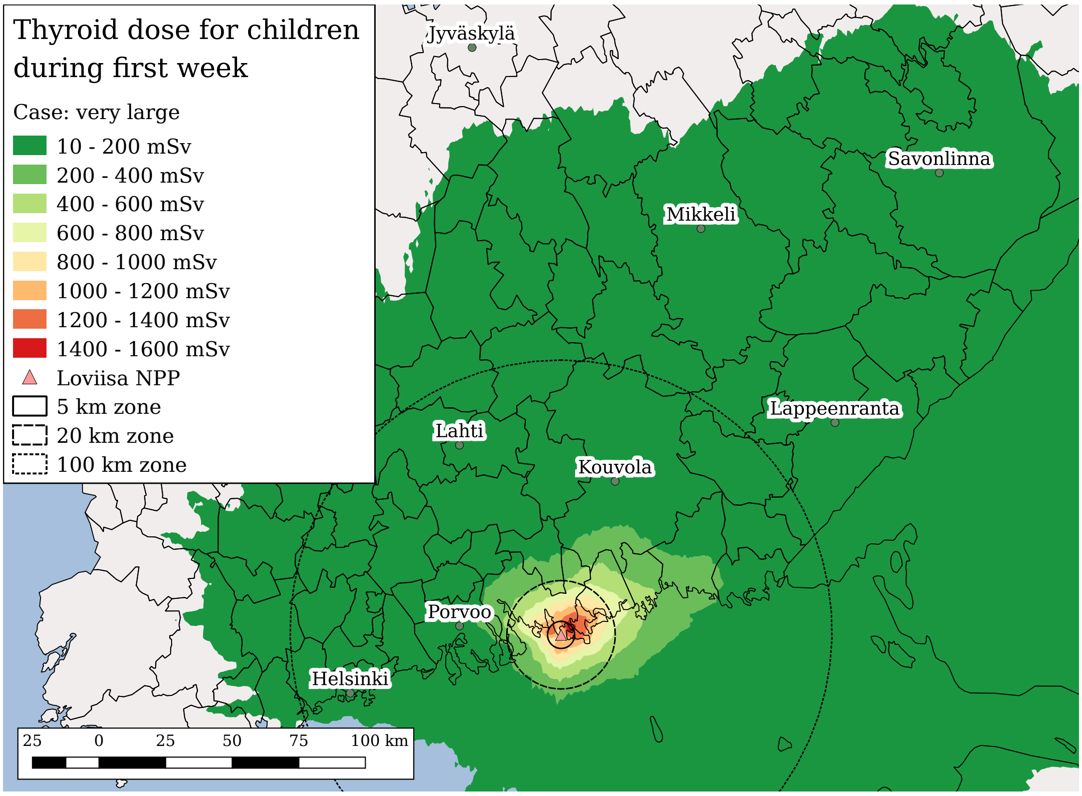

Figure 8.32: Thyroid dose for 1 year old unprotected children during first week in Loviisa very large case.

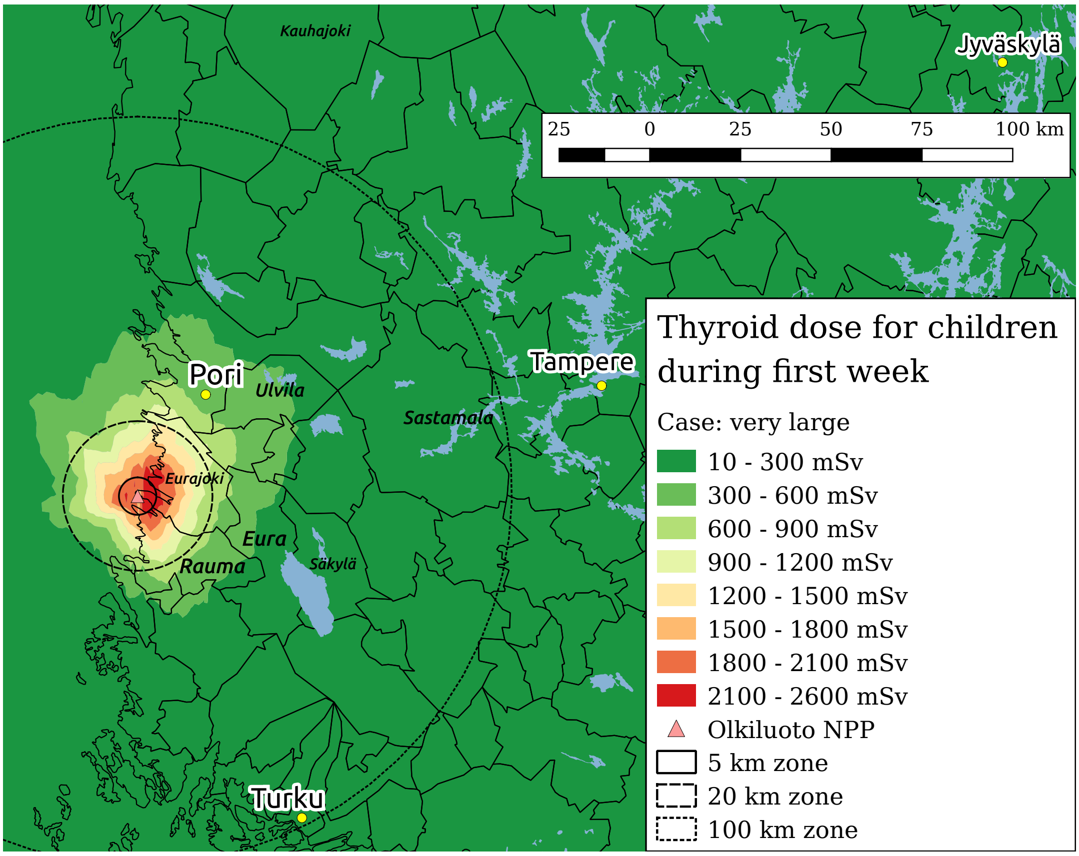

Figure 8.33: Thyroid dose for 1 year old unprotected children during first week in Loviisa very large case.

Chapter 9

Conclusions

Based on the results of this study, the current emergency planning zones are sufficient in most weather and release scenarios. Only the very large release scenario showed the need for protective actions outside the EPZ with respect to several studied operational intervention levels. For these areas, further study and possibly some further emergency planning for nuclear power plant accidents are in order. Large and basic cases show less severe consequences. The basic case does not have nearly any significant consequences and for the large case those stay within the 20 km zone.

Results show that some of the dose criteria and operational intervention levels are not consistent with each other. For example, during the first 48 hours the external dose rate exceeds the operational intervention level in the very large case for significant periods of time, but the dose criterion for sheltering is not exceeded. This stresses the uncertainty in the dose calculations and overall evaluations in a nuclear emergency. Consistency is shown between the strong gamma emitter deposition and the external dose for children during the first week. At this point of view, the operational intervention level serves its purpose protecting the children.

9.1 Future research

A broader dose calculations analysis would offer more intake to comparison with the operational intervention levels. This analysis could include several other time ranges for dose calculations, for example multiple different 48 hour slots at different phases of the accident.

The similar analysis of this thesis can be performed to the new Finnish NPPs: Olkiluoto 3 and Hanhikivi 1. The same method can be applied to possible analysis on consequences of small modular reactor related accidents and to NPP sites in the neighbouring countries. SMR and foreign NPP site analysis would require review on the weather model areas and parameters, but otherwise the model should be directly suitable.

For future research topics this thesis would also suggest sensitivity analysis on choosing the weather scenarios, i.e. the effect of the chosen weather data percentile. Another point of view is how the different seasons affect the results, should there be different preparedness in the summer than in the winter.

Chapter 10

Summary

The goal of this thesis was to study potential consequences of hypothetical nuclear power plant accidents at operating Finnish reactor units in Loviisa and Olkiluoto. Purpose was to find out how the magnitude of release affects the consequences and are the emergency preparedness zones suitable for these releases. Operational intervention levels and dose criteria for the protective actions were also compared.

Consequences were assessed using historical weather data from years 2012-2015. Weather data was collected with AROME and HARMONIE forecast models. The weather data acted as an input for dispersion and deposition calculations for three release scenarios – basic, large, and very large – executed with SILAM dispersion model. Doses and dose rates were calculated with STUK's threat assessment tool TIUKU. The SILAM and TIUKU outputs were post processed with Python 2.7 and its libraries. Map products were created using QGIS.

Depositions, air concentrations, and dose rates were calculated. Based on these, doses, effective dose and thyroid dose were calculated for unprotected adults and one year old children with 48 hour and 7 day integration time interval from the release.

The results show that emergency planning zones are suitable for most weather and release scenarios. Protective actions are needed outside the EPZ significantly only in the very large case. Basic case showed practically no need of invasive protective actions. Large release would probably require protective actions within the emergency planning zone. Doses during first 48 hours were not significant so the consequences were approximated with the 7 day dose.

The dispersion calculation related data was found feasible and consistent with the weather model. This leads to conclusion that the results are reliable and can be used for further studies and analysis on emergency preparedness planning.

Guidelines for future research for this topic could be calculating doses with several 48 hour time intervals in different phases of an emergency to determine the need for protective actions based on dose criteria. Furthermore, a more thorough comparison with operational intervention levels would be possible as well. Sensitivity analysis on choosing weather scenarios and dependence of the season would be another interesting points of view on this topic.

Similar analysis can be done to the new Finnish NPPs, Olkiluoto 3 and Hanhikivi 1. This model can be applied to accident analysis of the neighbouring country NPPs and to EPZ assessment of small modular reactors as well with adjustments to the weather model.

Bibliography

[1] Radiation act 859/2018. URL https://www.finlex.fi/fi/laki/alkup/2018/20180859. In Finnish.

[2] Emergency powers act 1080/1991. URL https://www.finlex.fi/fi/laki/kaannokset/1991/en19911080_20030696.pdf.

[3] Rescue act 379/2011. URL https://www.finlex.fi/fi/laki/kaannokset/2011/en20110379.pdf.

[4] J. Lahtinen, H. Toivonen, R. Pöllänen, and G. Nordlund. *STUK-A113 – A hypothetical severe reactor accident in Sosnovyy Bor, Russia: Short-term radiological consequences in southern Finland.* STUK, 1993. ISBN 951-47-8613-0.

[5] Mikko Ilvonen, Jukka Rossi, and Mika Salonoja. *Sosnovyi Borin aiheuttama säteilyriski Suomessa*. Valtion teknillinen tutkimuskeskus, VTT, 1994. ISBN 951-38-4673-3.

[6] J. Lahtinen, H. Toivonen, and R. Pöllänen. *STUK-A228 – Vakavan ydinvoimalaturman aiheuttamat säteilyseuraukset.* STUK, 1993. ISBN 951-47-8613-0.

[7] Jan Johansson, Peder Kock, Jonas Boson, Simon Karlsson, Patrick Isaksson, Jonas Lindgren, Elisabeth Tengborn, Anna Maria Blixt Buhr, and Ulf Bäverstam. *Review of Swedish emergency planning zones and distances*. 2018. Swedish Radiation Safety Authority. Report number 2017:27e.

[8] Tarja K. Ikäheimonen, editor. *Säteily ja sen havaitseminen*. 2002. ISBN 951-712-503-8. Part of the *Säteily- ja ydinturvallisuus* book series published by STUK. In Finnish.

[9] G.C. Lowenthal and P.L. Airey. *Practical applications of radioactivity and nuclear radiations*. Cambridge University Press, 2001. ISBN 0-521-55305-9.

[10] Thormod Henriksen and H. David Maillie. *Radiation and Health*. Taylor & Francis, 2003. ISBN 0-415-27161-4.

[11] Harri Toivonen, Tapio Rytömaa, and Antti Vuorinen, editors. *Säteily ja turvallisuus*. Säteilyturvakeskus ja Valtion painatuskeskus, 1988. ISBN 951-860-933-0. In Finnish.

[12] G. Audi, A.H. Wapstra, and C. Thibault. *Nuclear Physics*, 729(1):337–676, 2003. doi: https://doi.org/10.1016/j.nuclphysa.2003.11.003.

[13] Eric Neil Jenkins. *Radioactivity: a science in its historical and social context*. Wykeham Publications, 1979. ISBN 0-85109-7308.

[14] Roy Pöllänen, editor. *Säteily ympäristössä*. 2003. ISBN 951-712-995-5. Part of the *Säteily- ja ydinturvallisuus* book series published by STUK. In Finnish.

[15] Wendla Paile, editor. *Säteilyn terveysvaikutukset*. 2002. ISBN 951-712-506-2. Part of the *Säteily- ja ydinturvallisuus* book series published by STUK. In Finnish.

[16] United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation – volume II: Effects, 2000. URL `http://www.unscear.org/unscear/en/publications/2000_2.html`. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes.

[17] Jorma Sandberg, editor. *Ydinturvallisuus*. 2004. ISBN 951-712-507-0. Part of the *Säteily- ja ydinturvallisuus* book series published by STUK. In Finnish.

[18] K.S. Krane. *Introductory Nuclear Physics*. Wiley, 1987. ISBN 9780471805533.

[19] J.S. Lilley. *Nuclear physics: principles and applications*. Manchester physics series. J. Wiley, 2001. ISBN 9780471979357.

[20] Roy Pöllänen. *Nuclear fuel particles in the environment – characteristics, atmospheric transport and skin doses*. PhD thesis, University of Helsinki, Department of Physical Sciences, Faculty of Science, 2002.

[21] Fortum Oyj. Voimalaitoksen toiminta, . URL `https://www.fortum.fi/tietoa-meista/yhtiomme/energiantuotantomme/voimalaitoksemme/loviisan-voimalaitos/voimalaitoksen`. Retrieved: 18.5.2019.

[22] Teollisuuden Voima Oyj. Rakenne ja tekniset tiedot, . URL `https://www.tvo.fi/rakenneol1ol2`. Retrieved: 18.5.2019.

[23] VAL guide 1: Protective measures in early phase of a nuclear or radiological emergecy, 2011. URL `www.finlex.fi/data/normit/41315-VAL1.pdf`. In Finnish.

[24] VAL guide 2: Protective measures in intermediate phase of a nuclear or radiological emergecy, 2011. URL `www.finlex.fi/data/normit/41316-VAL2.pdf`. In Finnish.

[25] STUK, SSM, and NRPA et.al. Protective measures in early and intermediate phases of a nuclear or radiological emergency – nordic guidelines and recommendations, 2014. URL `https://www.stuk.fi/documents/12547/103518/nordic_flagbook_february2014.pdf/`.

[26] Regulation on the emergency arrangements of a nuclear power plant, stuk y/2/2018. URL `https://www.stuklex.fi/en/maarays/stuk-y-2-2018`.

[27] Silam homepage. URL `http://silam.fmi.fi/`. Retrieved 23.4.2019.

[28] Julius Vira, Niina Niinimäki, and Markku Seppänen. Uhkakuva-analyysit: leviämislaskentojen kuvaus. Private communications.

[29] Lisa Bengtsson, Ulf Andrae, Trygve Aspelien, Yurii Batrak, Javier Calvo, Wim de Rooy, Emily Gleeson, Bent Hansen-Sass, Mariken Homleid, Mariano Hortal, Karl-Ivar Ivarsson, Geert Lenderink, Sami Niemelä, Kristian Pagh Nielsen, Jeanette Onvlee, Laura Rontu, Patrick Samuelsson, Daniel Santos Muñoz, Alvaro Subias, Sander Tijm, Velle Toll, Xiaohua Yang, and Morten Ødegaard Køltzow. The harmonie–arome model configuration in the aladin–hirlam nwp system. *Monthly Weather Review*, 145(5):1919–1935, 2017. doi: 10.1175/MWR-D-16-0417.1. URL https://doi.org/10.1175/MWR-D-16-0417.1.

[30] M. Sofiev, J. Vira, R. Kouznetsov, M. Prank, J. Soares, and E. Genikhovich. Construction of the silam eulerian atmospheric dispersion model based on the advection algorithm of Michael Galperin. *Geoscientific Model Development*, 8(11):3497–3522, 2015. doi: 10.5194/gmd-8-3497-2015. URL https://www.geosci-model-dev.net/8/3497/2015/.

[31] M. Sofiev, P. Siljamo, I. Valkama, M. Ilvonen, and J. Kukkonen. A dispersion modelling system silam and its evaluation against etex data. *Atmospheric Environment*, 40(4):674 – 685, 2006. ISSN 1352-2310. doi: https://doi.org/10.1016/j.atmosenv.2005.09.069. URL http://www.sciencedirect.com/science/article/pii/S1352231005009271.

[32] Rostislav Kouznetsov and Mikhail Sofiev. A methodology for evaluation of vertical dispersion and dry deposition of atmospheric aerosols. *Journal of Geophysical Research: Atmospheres*, 117(D1), 2012. doi: 10.1029/2011JD016366. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011JD016366.

[33] John H. Seinfeld and Spyros N. Pandis. *Atmospheric Chemistry and Physics*. John Wiley & Sons, Inc, 1997. ISBN 0-471-17815-2.

[34] Kirsti Jylhä. Empirical scavenging coefficients of radioactive substances released from chernobyl. *Atmospheric Environment. Part A. General Topics*, 25(2):263 – 270, 1991. ISSN 0960-1686. doi: https://doi.org/10.1016/0960-1686(91)90297-K. URL http://www.sciencedirect.com/science/article/pii/096016869190297K.

[35] Private communications with Tuomas Peltonen, 10/2018-05/2019.

[36] Nina Petoussi-Henss, H Schlattl, M Zankl, A Endo, and K Saito. Organ doses from environmental exposures calculated using voxel phantoms of adults and children. *Physics in Medicine and Biology*, 57(18):5679–5713, 2012. doi: 10.1088/0031-9155/57/18/5679.

[37] ICRP database of dose coefficients v. 3.0. URL http://www.icrp.org/page.asp?id=402.

[38] Karlsruhe Institute of Technology. JRodos homepage. Retrieved: 3.5.2019.

[39] C.H. Clement, K. Eckerman, J. Harrison, H-G. Menzel, and C.H. Clement. ICRP, 2012. compendium of dose coefficients based on ICRP publication 60. ICRP publication 119. ann. ICRP 41(suppl.). Technical report, 2012.

[40] Python NetCDF4 module documentation. URL `https://unidata.github.io/netcdf4-python/netCDF4/index.html`. Retrieved 1.2.2019.

[41] Python NumPy library homepage. URL `https://www.numpy.org/`. Retrieved 1.2.2019.

[42] Python csv library homepage. URL `https://docs.python.org/2/library/csv.html`. Retrieved 1.2.2019.

[43] QGIS documentation. URL `https://docs.qgis.org/2.18/en/docs/`. Retrieved 1.2.2019.

[44] InkScape homepage. URL `https://inkscape.org/`. Retrieved 1.2.2019.

[45] Emlyn Howard Lloyd. *Handbook of Applicable Mathematics – Volume 6: Statistics*. Wiley, 1984. ISBN 0 471 90024 9.